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Finnish energy system modelling: renewable energy integration and future scenarios

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ABSTRACT OF THE
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Due to the climate change, there is a growing trend of decarbonizing the energy production, and Finland has ambitious goals in its transition from fossil fuels to renewable energy. In this work, we modelled the Finnish energy system on a macro level in 2013, 2030 and 2050. Both electricity, heat and fuel demands were included in the analysis, as well as five user sectors, two different consumption and two production scenarios: business-as-usual and the government programme. A special focus was given to the advanced conversion technologies between the final energy types, the so-called P2X. Electricity and heat were modelled on an hourly level, and fuels on a yearly level.

In all future scenarios, biomass and nuclear power will form the backbone of the Finnish energy system and the role of combined heat and power will decrease. However, it was found out that the renewable-oriented government programme scenario resulted in lower system costs and carbon dioxide emissions than the business-as-usual scenario. However, we were not able to reach all the government goals for energy self-sufficiency and renewable energy. In addition to these scenarios, we studied the effect of advanced conversion technologies on the maximum integration of wind and solar power.

Keywords: Energy system model, renewable energy, energy scenarios, P2X, energy, Finland

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Ilmastonmuutoksen takia energiantuotantoa on alettu muuttaa hiilivapaaksi, ja Suomella on kunnianhimoiset tavoitteet siirtyä fossiilisista polttoaineista uusiutuvaan energiaan. Tässä työssä mallinnettiin Suomen energiajärjestelmää makrotasolla vuosina 2013, 2030 ja 2050. Työssä otettiin huomioon sekä sähkön, lämmön ja polttoaineen kulutus, samoin kuin viisi kuluttajasektoria, kaksi kulutusskenaariota ja kaksi tuotantoskenaariota: "business-as-usual" ja hallitusohjelma. Erityistä huomiota kiinnitettiin kehittyneisiin konversiotekniikoihin eri energiamuotojen välillä, eli niin kutsuttuun P2X:ään. Sähkö ja lämpö mallinnettiin tunnin tarkkuudella, kun taas polttoaineet mallinnettiin vuositasolla.
Kaikissa tulevaisuuden skenaarioissa biomassa ja ydinvoima muodostavat Suomen energiajärjestelmän selkärangan ja sähkön ja lämmön yhteistuotannon rooli pienenee. Tuloksista kuitenkin havaittiin, että uusiutuvaa energiaa painottava hallitusohjelmaskenaario johti matalampiin kustannuksiin ja hiilidioksidipäästöihin kuin "business-as-usual". Hallituksen tavoitteita energiaomavaraisuudesta ja uusiutuvasta energiasta ei kuitenkaan saavutettu. Näiden skenaarioiden lisäksi työssä tutkittiin edistyneiden konversiotekniikoiden vaikutusta tuuli- ja aurinkovoiman integraatioon.

Avainsanat: Energiajärjestelmämalli, uusiutuva energia, energiaskenaariot, P2X, energia, Suomi

Preface

I want to thank Professor Peter Lund for introducing me to this topic and setting me on a career path ultimately leading to a PhD. I wish to thank Prof. Lund also for his guidance throughout the work related to this thesis. I would also like to say my thanks to the whole New Energy Technologies research group at Aalto University Department of Applied Physics where I have worked since 2012, and will continue to work in future. You have been providing the best work environment that any student could hope for. In particular, I wish to thank Dr. Janne Halme, Mr. Henri Vahlman and Dr. Antti Kaskela, who have instructed me in my special assignments and Bachelor's Thesis.

I also wish to thank all my fellow students in the Guild of Physics for the great study atmosphere during my studies and the fantastic freetime activities. My study years would not have been the same without you. Furthermore, I wish to thank everybody in the Polytech Orchestra for the amazing time we've had. PO has been the backbone of my student life, and I'm already looking forward for the coming years.

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Otaniemi, 5.1.2016

Sannamari Pilpola

Contents

Symbols and abbreviations

Symbols

α	share in primary energy (%)
C	cost (€)
D	demand (TWh or TJ)
η	conversion efficiency (%)
E	energy output (TWh)
L	loss (TWh)
P	primary energy (TJ), production (TWh)
s	storage change (TWh)
S	storage level (TWh)
T	temperature (°C)
t	time (h)

Abbreviations

BAU	business as usual
BtL	biomass-to-liquid
CHP	combined heat and power
CO_2	carbon dioxide
DH	district heating
E2T	electricity-to-thermal
GDP	gross domestic product
GOV	government programme
IEA	International Energy Agency
M€	one million euros
O&M	operation and maintenance
PV	photovoltaics
P2G	power-to-gas
P2L	power-to-liquid
P2X	power-to-X, i.e. advanced conversion
RES	renewable energy source
TJ	terajoule, unit of energy
TWh	terawatt hour, unit of energy
VRE	variable renewable energy

Chapter 1

Introduction

Due to the greenhouse-gas-induced climate change, there is a global trend of decarbonizing the energy production, with the renewable technologies at the front line. The current goal of the International Energy Agency is to limit the global temperature rise to 2 °C. On the global level, the energy intensity of GDP and the carbon intensity of primary energy both have to be reduced by around 60 % by 2050 compared with today. However, the recent trends towards the energy transition are promising but not enough to meet the target. [1]

The renewable energy markets are facing a major turning point, as renewable energy is approaching the grid parity limit in a increasing number of countries. At the same time, the prices of fossil fuels have decreased and the public support for renewable technologies has been cut [1]. This has resulted in a situation where the benefits of CO_2 emission reductions are no longer enough to drive the energy transition. To further enable the trend towards low-carbon energy economies, new kinds of market frameworks and government policies are needed.

In the European Union scale, the so-called 20-20-20 target is that 20 % of energy production should come from renewable sources, greenhouse gas emission should be reduced by 20 % and energy efficiency should be increased by 20 % by the year 2020. Finland is one of the most successful EU states in meeting its given goal, 38 %, as in 2014, the share of renewable sources in energy production was already 35 % [2]. While the current governmental policy is to maintain this goal, increasing the share of renewables beyond the 38 % has also attracted more and more attention [3].

For 2030, the targets are increasingly ambitious. The EU targets for 2030 are a 40 % cut in greenhouse gas emissions compared to the 1990 levels, at least a 27 % share of renewable energy consumption and at least 27 % energy savings compared with the business-as-usual scenario [4], whereas the goals of the Finnish government programme include for example abandoning coal in energy production and cutting the oil import in half [5].

In order to support the government in the Finnish energy transition, extensive research on the required incentive strategies should be conducted. For this purpose, both technological and economical modelling is needed. First, the technological feasibility of integrating large amounts of renewable energy should be studied. Secondly, the economic factors arising from price and incentives would need to be included. In the end, we would be able to determine the economic support needed to achieve the renewable scenario and the time scale of the transition, which would, in turn, help to formulate recommendations for policy-makers.

This thesis will focus on the technological aspect. The aim of this thesis is to study the effects of renewable energy integration into the Finnish energy system, taking into account the various new conversion methods between final energy types. A computer-based energy balance model is implemented for the purposes of this thesis.

This work is divided as follows. The second chapter provides background information related to the topics of this thesis. The third chapter describes the implemented energy balance model, and the research cases are presented in the fourth chapter. The fifth chapter lists the results of the study, and a summary and recommendations for future work are presented in the last chapter.

This thesis is part of Academy of Finland project DEFEND (Decentralizing Finland's energy regime: the triggers and dynamics of transition). The project is a multidisciplinary research consortium between Aalto University and University of Helsinki with the goal of "developing tools for triggering a transformation toward a sustainable energy regime, using Finland as a case study". The work related to this thesis was carried out in the New Energy Technologies Group of the Department of Applied Physics at Aalto University School of Science during the second half of 2015.

Chapter 2

Background for the model

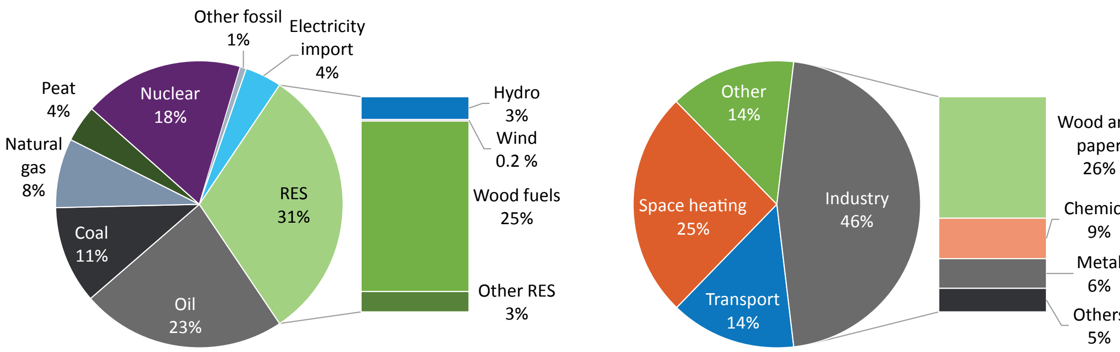
The chapter aims to provide background knowledge for the implemented energy balance model. The energy balance model will focus on the Finnish energy system and renewable energy integration utilising advanced conversion methods. In order to understand the operational environment of the model, this chapter will discuss the Finnish energy system in more detail, provide a short review of existing energy system models and, lastly, present the technical background of the advanced conversion methods.

2.1 Finnish energy system

Finland is a Nordic country with a cold climate and a limited amount of domestic energy resources. Finland's economy is also highly industrialised, with sizeable high-tech manufacturing, electronics and chemical sectors operating alongside a significant forestry and paper industry [6]. Because of the energy-intensive industries and the cold climate, Finland's energy consumption per capita is very high. According to the World Bank, Finland has the sixth-highest energy use per capita, topped by Iceland, Luxembourg, Canada, United States and Norway [7].

However, Finland has also a very high share of renewable energy. In 2013, 36.8 % of the Finnish final energy consumption was from renewable sources [2]. This level is one of the highest in the EU, topped only by Sweden and Latvia [8]. Wood-based fuels, such as forest chips and black liquor, are currently the main source of renewable energy, forming almost 80 % of the Finnish renewable energy sources, followed by hydropower (11 %) [9]. Finland is one of the leading countries in biomass use for energy production, and biomass accounts for approximately 25 % of the Finnish total energy consumption [2]. The wood-based biomass is mainly produced in the forest and paper industry, as a side product of the industrial processes, making it an appealing renewable energy source. Biomass is indeed considered as the backbone of fuel consumption in Finland's future renewable scenarios [3]. The shares of different primary energy sources are illustrated in Fig. 2.1a.

Despite the high share of renewable energy sources, electricity generation in Finland is dominated by nuclear and fossil production, as well as electricity import. Figure 2.2 shows the electricity generation mix of Finland compared to other Nordic countries and Germany in 2014. In Finland, one third of the electricity production was



(a) The shares of primary energy sources [2] (b) Final energy consumption by sector [10]

Figure 2.1: The Finnish energy mix in 2013.

covered by nuclear energy, one fourth with fossil sources, one fifth with hydropower and one sixth with biomass. The share of wind was only 2 %, whereas the total share of renewables was 36 %. 19 % of electricity demand was covered by net imports from other Nordic countries and Russia. As for quantities, the production of electricity in Finland amounted to 68.3 terawatt hours (TWh), and the total electricity consumption was 84.0 TWh [11].

In the neighbouring countries, the electricity mix has a lot variation between countries, making a direct energy system comparison between the countries more difficult. Sweden relies on nuclear and hydro power, whereas Norway relies almost solely on hydropower. In Denmark, wind power and fossil fuels are almost equally covering electricity production, whereas in Germany the electricity mix is more fossil-dominant. Since wind and hydropower are vulnerable to unfavourable wind conditions and droughts, having a well-functioning electricity market, Nord Pool, between the Nordic countries is especially important to smooth the variation in renewable energy production [6]. Within Nord Pool, Finland acts as both importer and exporter, but in general Finland is net importer of electricity.

The energy consumption in Finland is affected by the two major Finnish energy system characteristics: the cold climate and the energy-intensive industry. The final energy consumption by sector is illustrated in Fig. 2.1b. The industrial sectors accounts for approximately one half of the final energy consumption, the most energy-consuming industries being wood and paper, chemical and metal industries. One fourth of the final energy is used in space heating, which can be explained by the cold climate and the fact that space heating is needed for almost nine months a year [13]. Approximately 14 % of final energy is used in transport, and the rest, 14 %, for purposes other than industry, space heating or transport.

The same two reasons are also partly responsible for the prominence of combined heat and power (CHP) and district heating (DH) in Finland. Finland is a long-established global frontrunner in combined heat and power and district heating, and the overall high level of CHP utilisation has been market driven with little direct government support [13]. In 2013, CHP accounted for 27 % of electricity demand and

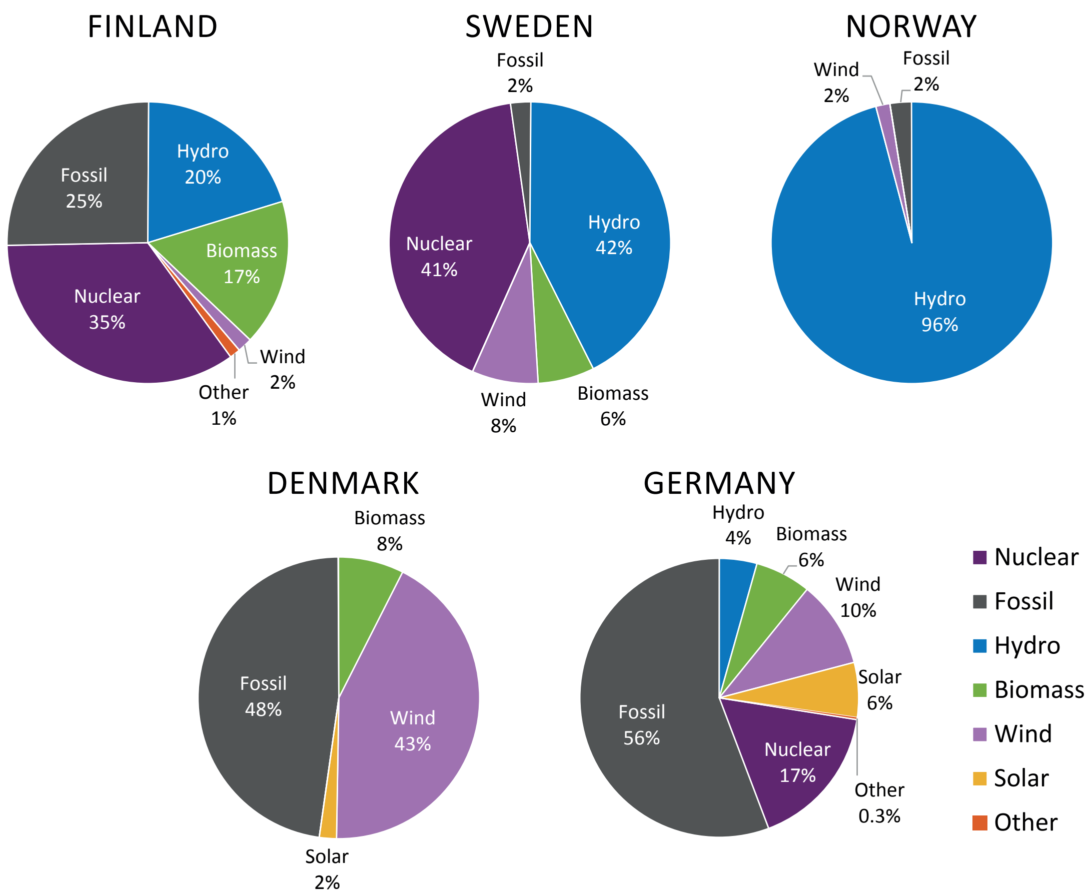


Figure 2.2: Electricity generation mix in 2014 in several Nordic countries. [12]

46 % of space heating demand [14]. Overall, district heating is the most common form of heating in Finland, and according to Finnish Energy, almost 95 % of apartment buildings and most public and commercial buildings are connected to the district heating network. In the largest cities, the market share of district heating is more than 90 %.

In addition to district heating, CHP is also widely used in forest industry, where the industrial CHP produces both electricity, industrial heat and partly also district heat. In the Finnish statistics, CHP is thus categorized as district heating CHP and industrial CHP. In 2013, approximately one half of the district heat (the total being 34.5 TWh) was produced by renewable sources, whereas of the industrial heat (52.2 TWh in total) over 70 % was from renewable sources [2]. The main renewable source for industrial heat was black liquor and other wood-based waste produced by the forest industry, and the forest industry is also the main user of the industrial heat. Therefore, we can state that the forest industry, as well as other process-based industry, forms a major party in the Finnish energy system, both in the supplier and user side.

However, despite the high share of domestic biomass, Finland is highly dependent on energy import, including oil, coal, gas and electricity. For example in 2011, imports accounted for 78 % of the total energy supply, and most of the import originated from one single country, namely Russia. In terms of energy security, this poses a major challenge. It has been stated that a diversified portfolio of energy resources in a country decreases the overall risk of energy supply [15]. In order to ensure Finland's energy security, diversification and domestic sources, especially peat, have been promoted. At the same time, Finland is committed to its EU target of 38 % share of renewables by 2020. These two long-term goals are clearly intertwined as cleaner technologies and "decarbonisation" also benefits the energy security. [6]

The current government programme [5] aims to increase the share of renewable energy to over 50 % during 2020s and the self-sufficiency in renewable energy to more than 55 %, also including peat. According to the government, this will be based on bioenergy, especially liquid biofuels and biogas. Among other policy-related goals, coal will no longer be used in energy production and the use of imported oil for the domestic demands will be cut by half during the 2020s. The share of renewable transport fuels will also be raised to 40 percent by 2030, while in 2013 the share was 5 % [16].

To conclude this section, we can state that the main characteristics of the Finnish energy system are the high share of CHP and district heating, the energy-intensive industrial sector and the importance of biomass and forest industry, and that the Finnish energy targets are ambitious. The model aims to take these characteristics into consideration in its implementation.

2.2 Short review of existing energy system models

In order to plan the policies needed for renewable energy integration and securing energy supply, it is crucial to show how renewable energy can be implemented in the energy system. These technical analyses are usually done with a computer-based tool or a method, and the demand for computer tools has existed for a long time. As a result, a myriad of tools to model energy systems exist. A 2009 review by Connolly et al. [17] listed 68 different computer tools that could be used to analyse the integration of renewable energy.

According to the review [17], there is no energy tool that addresses all issues related to the integration of renewable energy, because the "ideal" energy tool is highly dependent on the specific objectives that must be fulfilled. However, long-term policy goals require energy models suitable for long-term scenarios, but the technical accuracy of long-term models may vary significantly. Desperés et al. [18] found out in their review of long-term models that even the most accurate long-term energy models lack a temporal representation of the power sector. Since long-term models often consider also other sector than electricity, electric grid, temporal constraints and possible electricity storage are modelled in less detail.

The methods of energy system modelling vary from technically and temporally detailed computer models [17] to system dynamics approach [15, 19], which takes the dynamic effect of energy policies into consideration. The categorization of energy models is difficult, and several categorizing methodologies exist [18, 20].

The extensive review by Connolly et al. [17], which is used as the basis of this chapter, divides computer models into simulation, scenario, equilibrium, top-down, bottom-up, operation optimization and investment optimization. A tool can represent several categories. A simulation tool simulates the operation of a given energy system to supply given energy demands, whereas a scenario tool produces long-term scenarios, usually with the timestep of one year. An equilibrium tool explains the behaviour of supply, demand and prices in an economy with several markets. A top-down model describes the macro-economic relationships in the whole economy in terms of growth, whereas bottom-up takes into account the technical and economic features of different energy technologies. The combination of top-down and bottom-up models are called hybrid [21], and they try to combine the macro-economic coverage of top-down and the technological detail of bottom-up.

2.2.1 Examples of computer tools

As a short review of the existing computer tools, we will now present five tools which have been used in the context of the Nordic countries: Balmorel, EFOM, EnergyPLAN, TIMES and WILMAR. All of these models have been used to model the Nordic countries on a national level, with a focus on future scenarios and renewable energy integration. If not otherwise stated, this section is based on the review by Connolly et al. [17].

Balmorel [22] is a partial-equilibrium tool including the electricity sector and CHP-based district heating. It is distributed as open source since 2000, and it is formulated in the GAMS modelling language. Balmorel's input data and results given in relation to a geographical subdivision, and the time scale is treated in a flexible way, as the timestep depends on the scenario length. Electricity transmission is described as a number of connected nodes, and bottlenecks can be identified. Balmorel is capable of both operation and investment optimization, including all costs of the energy system, while satisfying the demand for power and district heating. The disadvantage of Balmorel is the lack of the transport sector, although some studies have included electric vehicles [23].

EFOM (Energy Flow Optimization Model) [24], models the energy flows in the system. The energy system is represented as a network of energy chains, and the system is optimized by linear programming, using the total present value costs of the entire energy system over the whole study period as the objective function. EFOM was the supply part of the energy model complex of the Commission of the European Communities, and it was later incorporated into TIMES.

EnergyPLAN [25] is a user-friendly tool to simulate the entire energy system, including electricity, heat, transport and industry. It has been developed since 1999 at Aalborg University, Denmark. It is a deterministic input/output tool, with demands, renewable energy sources, energy station capacities, costs and import/export strategies as inputs and energy balances and costs as outputs. EnergyPLAN optimizes the operation of the system, not the investments, and the optimization is done with the timestep of 1 hour over one year. EnergyPLAN has been especially used in renewable energy integration studies.

TIMES (The Integrated MARKAL-EFOM System) [26], is a family of energy-economic-environmental tools, whose purpose is to represent the evolution of the system over a long time. TIMES is a GAMS-based commercial tool, developed under IEA since 1978. TIMES tries to minimize the total discounted system cost, including all sectors, all costs and the whole time horizon. Its input data, in the form of annual load duration curves, can be expressed as user-defined time slices. TIMES has been used, for example, to simulate European Commission policies and the 20-20-20 targets. The use of TIMES requires training for some months.

WILMAR Planning Tool (Wind Power Integration in Liberalised Electricity Markets) [27], is specifically focused on wind power, and its first version was created in 2006. WILMAR is used to analyse the optimal operation of a power system, while treating wind power production forecasts and load forecasts as stochastic input parameters. The optimization is done by minimizing the system operational costs, including e.g. fuel and start-up costs. Electricity storage is included, as well as district heating and electric vehicles from the heat and transport sectors. WILMAR has been used e.g. to simulate the integration of wind power to the Nordic energy system and Germany [28].

Advanced conversion methods, such as hydrogen conversion or power-to-gas, are usually not included in the older models. However, advanced conversion is present natively in EnergyPLAN. Additionally, advanced conversion methods have been incorporated to the existing models in some studies. Hydrogen conversion as a path for renewable energy integration in the Nordic countries has been modelled with Balmorel [29], and power-to-gas was included in MARKAL for studying hydrogen as energy storage in the UK [30].

2.2.2 Modelling the Finnish energy system

The Finnish energy system has already been subjected to various types of modelling. In 1996, the future of the Finnish energy system was analysed with EFOM [24]. The paper and pulp industry were given a special focus, and the model was used to provide policy strategies for CO_2 emission reduction.

VTT, who provides the supporting reports for the government related to energy scenarios and policies [31], uses a model called TIMES-VTT, which is a TIMES-based model modified for the Finnish conditions [32, 33]. The model is able to describe the whole energy system from primary energy to final energy demand, and the scenarios include for example economic growth, energy policies and technological development as variables. The model includes the exchange capacities within the Nordic countries, as well as fuel and emission permit markets. The model also takes into account a variety of sectors and their interactions. Additionally, new conversion technologies are taken into account to some unknown extent, including at least hydrogen production and biofuel conversion [32]. The Low Carbon Finland 2050 report by VTT [33], cited widely in this thesis, is based on TIMES-VTT.

Balmorel has also been applied to Finland. Kiviluoma and Meibom [23] used Balmorel to investigate the influence of wind power, electric vehicles and heat storage on system investments. However, their study included only electricity and district heat demand, and conventional transport or types of heating other than district heating were not included.

Recently, EnergyPLAN-based studies have been published at Aalto University (e.g. [3, 34, 35]) and Lappeenranta University of Technology [36]. Zakeri et al. [3] concluded that with today's demand, the maximum feasible renewable energy for Finland is around 44-50 % in final energy consumption, leading to +250 M€/year increase in the 2012 system costs. Child and Breyer [36] examined 100 % renewable scenarios in 2050 including power-to-gas and energy storage, and they found out that 100 % renewable scenarios are cost-competitive compared to the Business-as-usual scenario.

2.3 Advanced conversion methods

If a power system has a large share of intermittent energy sources, such as wind or solar, the number of hours where generation exceeds demand will increase, leading to so-called surplus power or electricity overproduction [37]. For this reason, there exists a variety of methods to utilize the electricity surplus for other purposes, for example heat, mobility, fuel or chemicals. These methods can be referred to as power-to-X or P2X, where P stands for surplus power and X for the energy form to which this excess electricity is converted to [38]. These methods have the potential to increase system flexibility and act as storage, which are needed in accommodating large amounts of intermittent renewable power.

This section will describe the different P2X methods considered in this thesis. In general, these advanced conversion methods, are they are also referred as, are methods capable of converting energy between final energy forms. They include electricity-to-thermal (E2T), power-to-gas (P2G), biofuel conversion and power-to-liquid (P2L).

2.3.1 Electricity-to-thermal

Electricity-to-thermal (E2T) refers to converting electricity into thermal energy. What makes E2T a simple, but efficient strategy for excess renewable electricity accommodation, is that heat demand generally dominates the final energy use, heat is easier to store than electricity and emissions are reduced due to E2T replacing the fossil-based heat production [38]. The main technologies for E2T are electric boilers and heat pumps. The maximum coefficient of performance (COP) for an electric boiler is 1, whereas for heat pumps COP is 2-3 for an air heat pump and 2.5-5 for a ground heat pump [37]. E2T has proven to be economical and fuel-efficient, and large-scale heat pumps are especially promising, whereas electric boilers are a low-cost solution [39].

2.3.2 Power-to-gas

Excess electricity can also be converted to fuels, such as hydrogen or synthetic methane, which in turn may be utilized as fuel, or even as storage, as synthetic methane could employ the existing gas distribution systems which have a large storage capacity [38]. This two-step process from electricity to synthetic natural gas is called power-to-gas (P2G). There are several technologies for P2G, but the main process is always similar: hydrogen production by water electrolysis and hydrogen conversion with an external CO or CO_2 source to synthetic methane via methanation [40]. Since carbon dioxide is used as the carbon source, P2G has the potential to avoid or reduce CO_2 emissions [37].

The first reaction is the hydrogen production with the reaction known as water splitting:

$$2\ H_2O \xrightarrow{\text{electricity}} 2\ H_2 + O_2, \tag{2.1}$$

where water (H_2O) is separated into hydrogen (H_2) and oxygen (O_2) via electricity. This reaction can be done by electrolysis, for example with alkaline electrolysis (AEL), polymer electrolyte membranes (PEM), and solid oxide electrolysis (SOEC) [40], or with photoelectrolysis, where light is used as the energy source. The resulting hydrogen can be directly used as fuel, but the alternative is the conversion to hydrocarbons with higher energy content. The currently most developed hydrogen conversion process is methanation with the so-called Sabatier reaction [37]:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy} \tag{2.2}$$

The Sabatier reaction is highly exothermic which leads to high conversion losses when the heat is not completely used [37]. However, the reaction heat has a high temperature, about 300 °C, and could be used for both industrial steam production and/or district heating [41]. The combined potential of synthetic fuel production, CO_2 emission reductions and heat production makes P2G a promising alternative in energy system decarbonisation.

2.3.3 Biofuel conversion and power-to-liquid

In addition to the electricity-consuming methods, we will also include two advanced conversion methods for transport fuel decarbonisation: biofuel conversion and power-to-liquid (P2L).

Biofuel conversion, or biomass-to-liquid (BtL), refers to the conversion from biomass to liquid biofuels. The first-generation biofuels, made from sugars, starch and other crops, are easily extracted using conventional technology, but the production of fuel from feedstock raises the controversy of competing with the demand for food. The second-generation biofuels are produced from various types of biomass. In Finland, the most suitable form of second-generation biofuels are lignocellulosic biofuels, made from wood-based biomass, which is an abundant domestic resource in Finland [42].

Technological know-how of second-generation lignocellulosic biofuels already exists in Finland, as biofuels offer an excellent opportunity for the Finnish forest industry. UPM recently opened a commercial biodiesel plant in Lappeenranta, using waste liquids of the forest industry as the raw material [43]. Their biodiesel production process is the Fischer-Tropsch process, where synthetic hydrocarbons are produced from a mixture of carbon monoxide and hydrogen, also called syngas:

$$(2n+1)\mathrm{H}_2 + n\mathrm{CO} \rightarrow \mathrm{C}_n\mathrm{H}_{2n+2} + n\mathrm{H}_2\mathrm{O}, \tag{2.3}$$

where n is an integer and $\mathrm{C}_n\mathrm{H}_{2n+2}$ represents the product that consists mainly of paraffinic hydrocarbons of variable chain length [44]. The Fischer–Tropsch process includes various processing steps, most importantly gasification [42], where the woody biomass is converted into syngas. The gasification is usually done in an oxygen-blown fluidised-bed gasifier, operating in high temperatures ($\sim$ 800 °C) [44].

Power-to-liquid (P2L) refers to the conversion from natural or synthetic gas to biofuel. There are several process for this conversion, including the already-described Fischer-Tropsch process. The natural gas, mostly composed of methane, is first converted into syngas via partial oxidation, and then to longer hydrocarbons via Fischer-Tropsch.

Chapter 3

Energy balance model

In this thesis, a computer model of the Finnish energy system was developed. The aim was to model the energy balance of Finland on a macro level with a particular focus on renewable energy additions and advanced conversion methods. The model builds upon the existing energy balance and energy systems, instead of building the whole energy system from scratch. Being a macro level model, the model considers Finland to be one single energy system, and most of the details within the Finnish energy system are not taken into account, such as electricity production on power plant level or system limitations. The balance model includes all the three end products of energy, namely electricity, heat and fuel.

The model ultimately aims to answer the question of how renewable energy sources could be included in the existing energy system. As already discussed in 2.1, the Finnish energy system has some defining characteristics: the large amount of CHP and the important role of industry. These attributes, which are very specific to Finland, comprise several boundary conditions to the energy balance model. Therefore, especially the requirements forest industry are included in the model.

The model covers the time period of one calendar year, but it operates on two temporal scales: annual and hourly. Electricity and heat production and consumption are modelled on an hourly level, whereas fuel is modelled on an annual level, as fuel includes an inherent storage capacity.

The model is implemented with Microsoft Excel, allowing a more user-friendly model. The model has been built with a "tabula rasa" approach: no existing models have been incorporated into the model in order to avoid possible historical burdens and to ensure a fresh modelling approach.

3.1 Structure of the model

The basic idea behind the model is shown in Fig. 3.1. The energy flow starts from the primary energy sources, such as oil and wind power. The conversion process from the primary sources to final energy is divided into two parts: the conventional methods, such as combined heat and power (CHP), and the advanced methods, such electricity-to-thermal (E2T). After the conversion processes, the resulting final energy is divided into three types: electricity, heat and fuel. This final energy will be matched to the demands coming from the different sectors. The five sectors used in

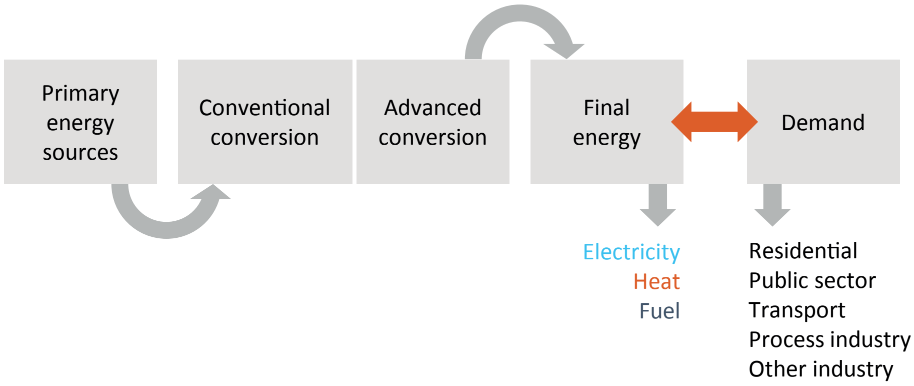


Figure 3.1: Basic idea of the model. The energy flow starts from the primary energy sources which will then undergo the conversion and advanced conversion processes. The resulting final energy i.e. electricity, heat and fuel is matched to the demand from the different sectors.

the model are residential sector which also includes agriculture, public sector, process industry which includes paper, metal and chemical industry, the rest of the industrial sector and transport.

A more detailed schematic of the model is shown in Fig. 3.2. The basic structure is the same previously, but the various modules within the stages are included. The module structure is loosely based on the division used by Statistics Finland, especially the categorization of primary energy sources. The primary energy sources included in the model are

- Oil
- Coal
- Natural gas
- Peat
- Biomass (wood-based)
- Waste-to-energy
- Nuclear power
- Hydropower
- Wind power
- Solar photovoltaics (PV)
- Solar heating
- Heat pumps
- Others

The "others" category used by Statistics Finland includes i.a. hydrogen and secondary heat from industrial processes. The two additional primary energy sources not yet included by Statistics Finland are solar PV and solar heating. Due to the Finnish energy system structure, the "biomass" category includes mostly wood-based biomass, such as black liquor, forest chips and industrial wood residue.

The first conversion phase includes the conventional heat and electricity production methods: separate heat and electricity production, combined heat and power (CHP) and residential heat production. Based on the division used by Statistics Finland, CHP is divided into CHP in energy industry, labelled "CHP-District heating" or "CHP-DH", and CHP in non-energy industry, labelled "CHP-Industrial" or "CHP-ind". Part of the primary energy sources naturally stay unconverted in this first conversion phase. Additionally, this conventional conversion phase could include other conversion types, such as oil refineries, but they are not included in the model. Oil refineries are considered only as throughput, and the model does not do any separation between the different oil products and raw oil.

The resulting energy after the first conversion is divided into three pools, namely electricity, heat and fuel. The possible imbalance between these mid-process balance nodes and final demand serve as motivation for the following advanced conversion methods. The advanced conversion methods, also labelled as P2X, include the methods capable of converting energy between final energy forms. In the model, the advanced methods include

- E2T: system-scale electricity $\rightarrow$ heat conversion
- E2T residential: residential electricity $\rightarrow$ heat conversion
- P2G: power-to-gas, electricity $\rightarrow$ synthetic gas conversion
- P2L: power-to-liquid, natural gas $\rightarrow$ fuel conversion
- Biofuel conversion: converting biomass into biofuel

Additionally, heat and electricity storages are also available in this stage. The model allows disabling these advanced conversion technologies from the block structure, to allow exploring different scenarios including only a selection of the P2X technologies. The list above could also include other advanced conversion methods, such as the conversion from biomass to biogas. However, biomass-biogas conversion was excluded from the model in this thesis, since the "biomass" category is assumed to consist of different types of organic resources, including biogas.

The final energy pools that are used in the balancing act between production and demand are electricity, heat and three types of fuel. Fuel is divided into industrial fuel i.e. the fuel used in the industrial processes, transport fuel and biomass for forest industry. As the Finnish forest industry sector form a major party in the Finnish energy system, its demands are modelled carefully. We assume that all the biomass used by the process industry, which is mostly wood-based fuels such as black liquor [45], is a side product from the industrial wood processes and, thus, cannot be avoided. Therefore, the biomass demand for the process industry forms its own fuel category to ensure that the industrial processes are not disturbed. This division of the industrial fuel demand is Finland-specific, and its exclusion would not affect the overall model.

Table 3.1: Building heating efficiencies [46]

Fuel	η
Wood	55 %
Peat	60 %
Coal	60 %
Light fuel oil	78 %
Natural gas	90 %

As for the units used in the model, the energy units used in the model are terajoule (TJ) and terawatt hour (TWh). TJ is used as a measure of primary energy, but once the energy is converted into heat or electricity, TWh is used.

3.2 Input data

3.2.1 Consumption data

The model is based on the actual energy balance of Finland, instead of building an energy system from scratch. This is also a more realistic approach since also in reality, new energy scenarios have to be built onto the existing system. The actual data about the primary energy sources, conversion and consumption is obtained from the energy balance sheet of Finland, provided by Statistics Finland each year [16].

While grouping the data into the model modules, only end-use demand and demand in power production are included. Raw material usage, inventory losses and statistical differences are excluded for simplicity. The transmission losses are included only for electricity and heat.

The model assumes that fuel is used as such only in industry and transport. In the model, the transport sector includes also the fuel demand of agricultural machinery, assumed to be approximately one third of the total agricultural energy demand [31]. The fuel usage in the residential and public sectors is assumed to be used only in heating, so the fuel demands of these sectors are converted into heat demand using the efficiencies in Table 3.1, which are also used by Statistics Finland. It is also assumed that all the oil used in residential and public sectors is light fuel oil, since the share of heavy fuel oil in building heating is relatively low, for example 7 % in 2013 [46]. Additionally, a part of the electricity is used for space heating, for example 13 TWh in residential buildings in 2013 [47]. This electricity consumption is also converted to heat demand by multiplying it with the residential E2T conversion efficiency $\eta_{\mathrm{RES-E2T}}$, assumed to be 95 %.

The energy balance sheet is also utilized to calculate the conversion efficiencies for the different power production methods. Table 3.2 shows the conversion efficiencies calculated from 2013 balance sheet as an example. The conversion efficiencies are calculated as the ratio of energy output and input, meaning that the conversion efficiencies refer to the conversion from primary resource to final energy and not to the theoretical conversion efficiencies such the Betz limit for wind power. As solar

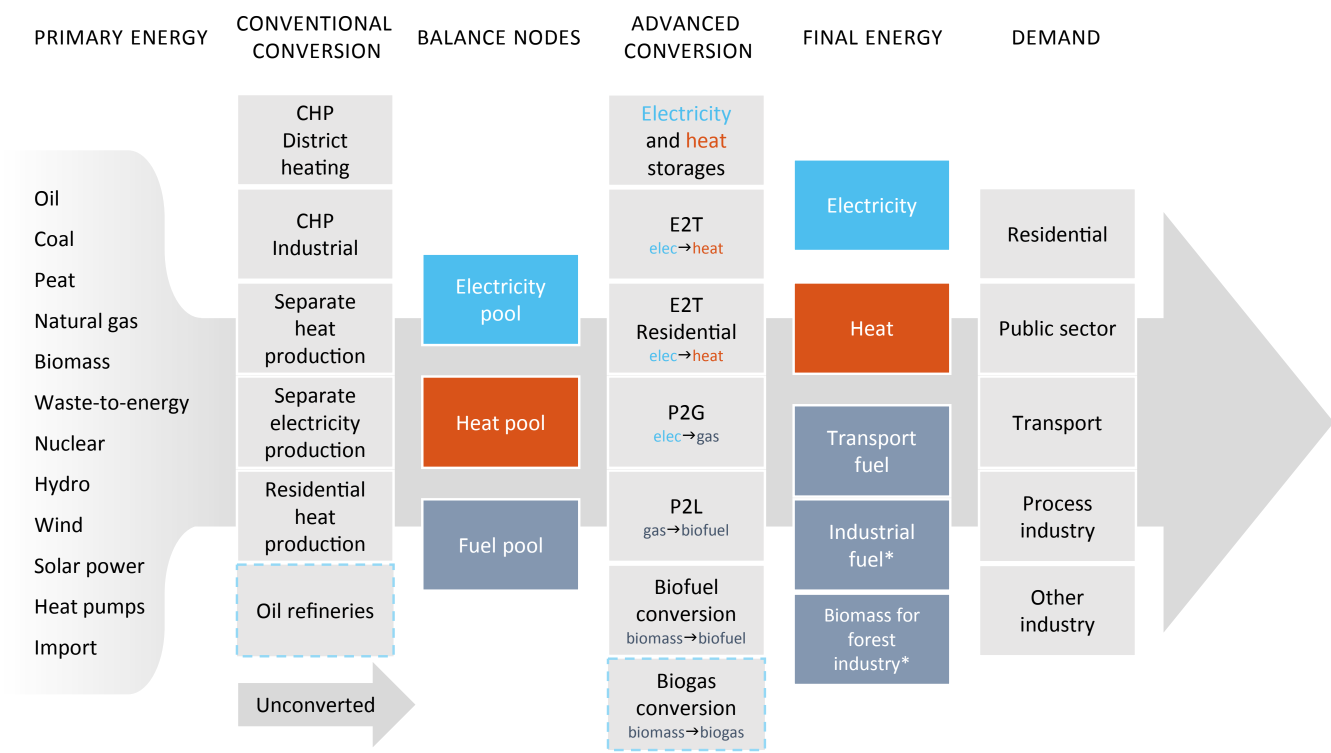


Figure 3.2: The block structure of the model. The primary energy sources are first converted by conventional methods, after which are the initial balance nodes for electricity, heat and fuel. The initial balance nodes are then modified by the advanced conversion methods. The resulting final balance nodes are electricity, heat and the three fuel categories, and these nodes are balanced to the demands from the different sectors. The blocks with dashed outlines (oil refineries and biogas conversion) are excluded from the model in this thesis, but included in this general structure for illustrative purposes. The fuel categories specific to Finland are marked with an asterisk (*).

Table 3.2: Conversion efficiencies from primary resources to final energy as in 2013 [16]

Production type	η
Nuclear	32 %
Hydro	99 %
Wind	100 %
Solar	100 %
Separate electricity	37 %
CHP-DH, elec	28 %
CHP-DH, heat	59 %
CHP-ind, elec	58 %
CHP-ind, heat	28 %
Separate heat	91 %

power is not yet included in the balance sheet, solar power conversion efficiency is assumed to be 100 %. In the case of industrial CHP, Statistics Finland applies the international statistical practise by which the production and consumption of heat include only heat sold or transferred outside, and the industrial steam not sold is not included in the model, nor in the efficiency calculations.

3.2.2 Heat demand

The hourly heat demand of Finland was calculated by a simple model based on outside temperature. The temperature measurements of one single weather station, Jyväskylä Airport, were used as an estimate of the average temperature of Finland. The temperature data was obtained from the Finnish Meteorological Institute [48], with a timestep of 1 hour.

The heat demand is modelled to have two components: a steady demand for domestic hot water and a temperature-dependent demand. The formula for heat demand $H(t)$ is

$$H(t) = H_0 + H_1 \cdot \max\{(T_{\text{ref}} - T(t)); 0\}, \text{while} \tag{3.1}$$

$$\sum_t H(t) = H_{\text{tot}} \tag{3.1a}$$

$$\min_t\ H(t) = \min_t\ H_{\text{ref}}(t) \tag{3.1b}$$

$$\max_t\ H(t) \leq \max_t\ H_{\text{ref}}(t) \tag{3.1c}$$

where H_0 is the constant term, H_1 is the varying term, $T(t)$ is the ambient temperature and $T_{\text{ref}} = 17$ °C is the reference temperature above which the varying term is zero. The sum of the hourly terms must be equal to the heat demand H_{tot} determined by the energy balance (Eq. (3.1a)). H_{ref} refers to the heat demand of Helsinki, scaled to match the total heat demand of Finland, based on consumption profile simulations by Jani Mikkola [49]. This reference heat demand is used give additional boundary conditions (3.1b)-(3.1c) for determining H_0 and H_1. The simulated heat demand is shown in Fig. 3.3.

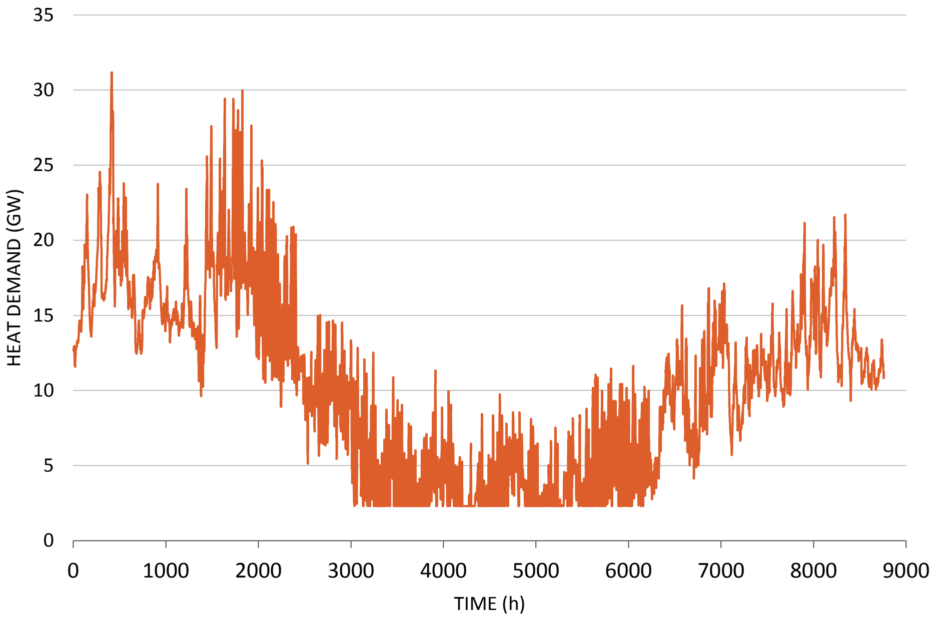


Figure 3.3: The simulated heat demand for one year (2013).

3.2.3 Electricity and heat production data

Hourly data about the Finnish electricity production is readily available from Finnish Energy (Energiateollisuus in Finnish) [50]. In the model, it is assumed that the shapes of the hourly production profiles do not change with varying output. Instead, the hourly production of each production method is scaled to match the annual total output as determined in the annual balance:

$$P_i(t) = P_{\text{orig},i}(t) \cdot \frac{\sum_t P_i(t)}{\sum_t P_{\text{orig},i}(t)}, \tag{3.2}$$

where $P_i(t)$ is the new hourly electricity production by method i, $P_{\text{orig},i}(t)$ is the hourly electricity production data for method i from [50] and $\sum_t P_i(t)$ and $\sum_t P_{\text{orig},i}(t)$ are their respective annual sums. The electricity production methods i that are included in the model are

- Hydropower
- Wind power
- Nuclear power
- CHP-District heating
- CHP-Industrial
- Separate thermal power
- Solar photovoltaics (PV)
- (Electricity storage and import)

The electricity consumption data is treated similarly as electricity production data: the hourly data is scaled to match the electricity consumption as determined in the annual balance by Statistics Finland energy balance sheet [16]. The only data category not obtained directly from Finnish Energy is electricity import, as it is calculated for each hour separately based on the imbalance of production and consumption.

There are, however, three exceptions: solar, wind and nuclear power. Since solar production is not yet included in the Finnish major statistics, the hourly production data is scaled from the data of a Helsinki 1 kW_p solar panel [51]. The same production profile is used for both solar PV and solar heat. Wind power data is obtained from Finnish Energy, as the other existing electricity production data, but since the wind capacity increased during the year, the production data was skewed. This capacity increase was smoothed out with a linear fit.

As for nuclear power, since Finland currently has two major nuclear power plants, the otherwise very flat hourly production profile has two distinctive gaps due to the annual service breaks. In future, the nuclear capacity of Finland is going to increase significantly with 1-3 new units (see Section 4.4.1). If the current nuclear production profile would be simply scaled to match the new capacity, the service breaks would not be realistic and they would cause major disruption in electricity production. It is unlikely that all the 4-7 units would be maintained at only two service breaks. Therefore, the nuclear production profile was modified by adding a third service break. The scaled nuclear production is then a combination of the two hourly production profiles, resulting in a more realistic nuclear power production profile with a higher number of power plants.

The last items on the list, electricity storage and import, can be seen as additional electricity production methods. They are utilized if the electricity production from the other production methods is not enough to meet the demand. The demand is first filled with electricity storage, if available, then import. More description about the storages can be found in 3.3.2.

Hourly heat data is obtained in a similar way as electricity, and the different heat production methods are:

- CHP-District heating
- CHP-Industrial
- Separate heat production
- Residential heat from fuels
- Residential heat from electric boilers (RES-E2T)
- Heat pumps
- Solar heat

And the advanced methods:

- E2T
- P2G
- (Heat storage)

It is assumed that CHP-based heat production follows the same hourly profile as CHP electricity production, albeit the differences between heat and electricity conversion efficiencies in CHP are taken into account. Solar heat production profile is the same as solar PV production, and residential heat production methods and heat pumps are assumed to follow the consumption profile. The hourly profile for separate heat production is calculated from the imbalance after heat consumption and production by the other methods, after the heat storage is taken into account, and the resulting profile is scaled to match the correct annual total. The heat storage is used if the other heat production methods are not enough to meet the heat demand, and its implementation is discussed in 3.3.1. E2T refers to system-scale electric boilers, whereas RES-E2T refers to residential electric heating.

It is acknowledged that the treatment of electricity and heat production data is a rough estimation. In reality, power plants are operated based on actual load and demand, and the hourly profiles would not follow the exactly same pattern at different production levels. However, calculating optimized hourly production data would require extensive optimization, which is outside the scale of this thesis. Therefore, it is assumed that simple production scaling is enough for the purposes of this model.

What should be also noted about assumptions is that the system limitations, such as the capacities of the Finnish electricity network, are excluded and only international exchange capacities are taken into account. It is assumed that Finland forms one single production and consumption area, and a more detailed geographical distribution is not included.

3.2.4 Cost assumptions

The model includes simplified cost calculations. The total costs of the energy system include capital costs, operation and maintenance (O&M), fuel costs, CO_2 emission costs and the cost of electricity import. However, the costs of electricity and heat grid are excluded, as transmission within Finland is excluded from the model.

Table 3.3 lists the fuel prices used in the cost calculations. It is assumed that most of the renewable primary energy sources are zero-cost, including wind, solar, hydro, waste-to-energy, heat from heat pumps, as well as the must-run biomass for process industry and industrial CHP, being mostly wood-based process waste. All taxes are excluded from this thesis, but in reality the taxation depends on whether the fuel is used in electricity or heat production. However, it is possible to include taxes in the model if needed.

The costs of the different technologies used in this study are listed in Table 3.4. The cost of a technology is divided into three components: investment cost per capacity (€/kW), fixed annual operation and maintenance costs (O&M) per capacity (€/kW) and variable O&M per energy output (€/MWh). Some of the technologies lack either the fixed or the variable O&M, depending on how the source in question communicated the cost information. The capacity of a certain technology is estimated as the maximum power output during the year, and the energy output is the annual total output. The annual investment cost is calculated by dividing the total investment

Table 3.3: Fuel prices in Finland in 2015. Fuel prices are retrieved from Statistics Finland [52], with the exception of nuclear fuel. The cost of nuclear fuel is the nuclear fuel cost in Finland according to IEA [53]. All fuels not listed are assumed to be zero-cost. Note that the biomass for process industry and industrial CHP are also assumed to be zero-cost, being mostly wood-based process waste. Biomass for other purposes has the price listed in the table.

Fuel	Cost (€/TJ)	Source
Oil	9 076	[52]
Coal	2 361	[52]
Natural gas	7 361	[52]
Peat	3 750	[52]
Nuclear	1 063	[53]
Biomass	6 028	[52]

cost by lifetime.

The cost assumptions are based on various sources, listed alongside the costs in Table 3.4. The cost data aims to be as accurate as possible, i.e. we have tried to retrieve cost assumptions for Finnish power plants if possible. There were some exceptions: wind power is estimated as Danish onshore wind, and solar PV is estimated as Danish commercial rooftop PV. As for the electricity storage, the electricity storage technology was assumed to be Li-ion batteries, since pumped hydro storage and compressed air energy storage (CAES) are assumed to be unfeasible in Finland due to the lack of suitable reservoirs. As for the biofuel conversion, the costs refer to lignocellulosic biofuel, which is the most suitable form of biofuel in the Finnish conditions.

Based on the various sources, the costs should be reported as cost ranges, rather than a single value. However, for the purposes of the model, only one value for cost type is included. The reported cost is merely a representative value based on the variation between different sources, and it is used for comparison between scenarios. Rather than absolute costs, the cost analysis focuses on relative cost difference.

The CO_2 emission costs are calculated based on the primary energy input. The specific carbon content of different fuels is listed in Table 3.5. It is assumed that nuclear, hydro, wind, solar, heat pumps and the category "others" have zero emissions. In addition, in this thesis it is assumed that all biomass is renewable, even though it produces carbon emissions. Currently, the emissions from land use, land use change and forestry sector do not come under the scope of the emissions trading scheme, which supports this assumption. However, for future use, the model includes the possibility of defining the share of renewable zero-emission biomass of the total biomass, ranging between 0-100 %.

The carbon price is heavily time-dependent, and Table 3.6 lists the carbon prices used in the model. The price projections are based on the International Energy Agency's 2 Degree Scenario (IEA 2DS) [1].

Finally, the cost of electricity import and, respectively, the revenues of electricity

Table 3.4: Cost assumption of different technologies, grouped by type. The source of the data is included in the rightmost column. Note that the cost of storage is listed differently to the rest. In case of ambiguity, wind power costs reflect on Danish onshore wind, solar PV on Danish commercial rooftop, electricity storage on Li-ion batteries and biofuel conversion on lignocellulosic biofuel. The costs do not include taxes.

Conversion technology	Investment cost	Fixed O&M	Variable O&M	Lifetime	Source
	€/kW_e	€/kW_e	€/MWh	years	
Hydropower	1 500	8	0	50	[3],[54]
Wind power	1 386	37	11.0	25	[53]
Nuclear power	4 000	40	0	50	[3]
Solar PV	1 538	17	8.2	25	[53]
CHP-DH	1 300	25	2.7	30	[23]
CHP-ind	1 300	25	2.7	30	[23]
Condensing power	1 300	52	0	35	[3]
	€/kW_{th}	€/kW_{th}	€/MWh	years	
Separate thermal prod.	150	9	1.5	35	[23]
RES-Heat from fuels	200	2	0	20	[3]
RES-E2T	40	1	0	40	[23]
Heat pumps	900	2	0	40	[23]
E2T	40	1	0	40	[23]
Solar thermal (inv. cost in €/MWh)	400	0	0.4	20	[3]
	€/kW_{input}	€/kW_{input}	-	years	
P2G	1 750	70	-	30	[36]
P2L	350	14	-	20	[3],[36]
	€/TJ_{output}	€/TJ_{output}	-	years	
Biofuel conversion	17 496	1 944	-	20	[44]

Storage	Capacity cost	Power cost	Annual O&M	Lifetime	Source
	€/MWh	€/MW	% of inv. cost	years	
Electricity	1 000	500 000	3 %	20	[53]
Heat	900	0	1 %	25	[3],[34]

Table 3.5: Specific carbon content of various fuels, according to Statistics Finland [55]. The data for oil is estimated as heavy fuel oil. All fuels not listed are assumed to have zero emissions.
* Biomass is considered completely renewable in this study, even though the specific carbon content of biomass (in brackets) is non-zero.
** The emissions from waste refer to the non-renewable part of waste.

Fuel	Carbon content (tCO_2/TJ)
Oil	78.8
Coal	93.3
Natural gas	55.0
Peat	105.9
Biomass*	0 (109.6)
Waste-to-energy**	31.8

Table 3.6: Carbon price projections, based on IEA 2DS estimates [1].

Year	Carbon price (€/tCO_2)
2013	8
2020	22.5
2030	60
2040	90
2050	105

export are calculated directly using historical Elspot price data from Nord Pool [56].

In case the source reported the values in USD, a fixed exchange rate of 1 USD = 0.75 EUR was used, the same as in IEA reports [53].

3.2.5 Other input data

Since the model allows international electricity exchange, exchange capacities have to be taken into account. The maximum exchange capacities of the Finnish electricity system in 2015 are listed in Table 3.7. In the future, Fingrid is planning capacity additions [57]. The Fenno-Russian capacity will be reinforced, allowing full two-way transmission by 2025. In addition, a third AC connection to Northern Sweden will be built by 2025, adding 700 MW of two-way capacity. After 2025, this study assumed that a third DC sea cable to Central Sweden (Fenno-Skan 3) would be built by 2050, adding 800 MW transmission capacity, and all the existing connections are reinforced to full two-way transmission.

Table 3.7: Maximum transfer capacities of the Finnish electricity system in 2015 [58] and future estimations. N. Sweden stands for Northern Sweden, and C. Sweden for Central Sweden, respectively.

Year	Region	Export (MW)	Import (MW)
2015	N. Sweden	-1 100	1 500
	C. Sweden	-1 200	1 200
	Russia	-320	1 460
	Estonia	-1 000	1 016
	Total	-3 620	5 176
2030	N. Sweden	-1 800	2 200
	C. Sweden	-1 200	1 200
	Russia	-1 460	1 460
	Estonia	-1 000	1 016
	Total	-5 460	5 876
2050	N. Sweden	-2 200	2 200
	C. Sweden	-2 000	2 000
	Russia	-1 460	1 460
	Estonia	-1 100	1 100
	Total	-6 760	6 760

3.3 Conversion

In conventional conversion, such as CHP, allocation of primary energy between the different power production methods is defined in each scenario manually, and there are no specific rules for it. The conversion itself follows the simple formula

$$E_i = \eta_i \cdot \sum_k P_{i,k}, \tag{3.3}$$

where E_i denotes the energy output, either electricity or heat, from the method i and $P_{i,k}$ denotes the allocation of primary energy sources k and η_i is the conversion efficiency for method i. In CHP, there are two separate outputs, electricity and heat, which both have their own conversion efficiency, but only one primary energy input. It should be noted that the conversion methods apart from hydro, nuclear, wind and solar power, which utilize only one self-explanatory primary energy source each, do not make a separation between different primary fuel sources and the same conversion efficiency is used regardless of the used primary energy sources.

In addition to the fuel-based conversion methods, there are two electricity-consuming conventional conversion methods: residential electric heating (RES-E2T) and heat pumps. Residential E2T aims to fill the missing residential and public heat demand, whereas heat pumps are considered a primary energy source, the amount of which is defined by the user. These methods consume electricity, and therefore must be included in the hourly electricity data. The electricity consumption of the existing RES-E2T and heat pumps is already present in the overall electricity consumption data, but the electricity consumption of additional RES-E2T and heat pumps has to be calculated separately. The electricity consumption is calculated based on the additional heat production, with conversion efficiencies $\eta_{\mathrm{RES-E2T}}$ and $COP_{\mathrm{heat\ pump}}$, respectively. The efficiency of heat pumps, $COP_{\mathrm{heat\ pump}}$, is assumed to be heat output divided by electricity consumption, i.e. the low temperature heat input from the surroundings is not included in heat pump efficiency calculations. The resulting additional electricity consumption is treated the same way as "normal" electricity consumption.

As for the non-conventional methods, the operation of advanced conversion and storages is entirely rule-based. The following subsections describe these operation rules, with codes as general pseudo-code. The actual codes are implemented in Microsoft Excel and with supplementary VBA-based macros.

3.3.1 Heat storage

The charging and discharging of the heat storage depend on the imbalance of heat production $P_{\mathrm{heat,tot}}$ and demand D_{heat}. All losses of the storage are simplified to a round-trip efficiency $\eta_{\mathrm{sto,heat}}$, taken into account in discharging. Storage losses over time are not considered in the scope of this thesis, but will be included in later versions. Charging and discharging power are not limited, and the storage level S_{heat} (TWh) is kept between 0 and maximum capacity $S_{\mathrm{heat,max}}$. The storage change s_{heat} is

$$s_{\mathrm{heat}}(t) = \max\left\{P_{\mathrm{heat,tot}}(t) - D_{\mathrm{heat}}(t); -\eta_{\mathrm{sto,heat}} \cdot S_{\mathrm{heat}}(t-1)\right\}, \tag{3.4}$$

where the limit $-\eta_{\mathrm{sto,heat}} \cdot S(t-1)$ refers to the available stored heat, and it ensures that the storage level does not drop under 0. A positive s_{heat} implies storage charging, and a negative s_{heat} discharging. The starting value of the storage, $S_{\mathrm{heat}}(0)$, is initially set to zero, but it can be changed. The storage level changes as

$$\begin{aligned}
&\text{if } (s_{\mathrm{heat}}(t) > 0) \\
&\qquad S_{\mathrm{heat}}(t) = \min\left\{S_{\mathrm{heat}}(t-1) + s_{\mathrm{heat}}(t); S_{\mathrm{heat,max}}\right\} \\
&\text{else} \\
&\qquad S_{\mathrm{heat}}(t) = \min\left\{S_{\mathrm{heat}}(t-1) - \frac{|s_{\mathrm{heat}}(t)|}{\eta_{\mathrm{sto,heat}}}; S_{\mathrm{heat,max}}\right\},
\end{aligned} \tag{3.5}$$

where the limit ensure that storage does not exceed the maximum capacity. In the case of heat storage, "overcharging" the storage is allowed i.e. $s_{\mathrm{heat}}(t)$ is not limited by the storage capacity, but the heat that cannot be stored is simply lost. This is due to the fact that unlike electricity, heat is assumed to be untransportable to international markets and the overproduction cannot be compensated by export.

It was noticed that heat storage is essential for system operation, so unlike electricity storage, it cannot be disabled. Based on the original 2013 scenario, the heat storage capacity that already exists in the Finnish energy system was assumed to be 0.05 TWh. This assumption is the same order of magnitude as the actual storage capacity of the Finnish DH-CHP networks, 0.017 TWh, and 2/3 of the Finnish DH-CHP is produced in networks with storage capacity [34].

3.3.2 Electricity storage

The electricity storage operates very similarly to the heat storage, with the exception that electricity can also be exported and imported. This allows using two different approaches for storage operation: 1. Storage operated independently from electricity exchange. 2. Storage operation depends on the electricity prices. The logic can be switched in the model, but in this study, only the first approach is used.

In the first approach, electricity storage operation is almost identical to heat storage, only overcharging is not allowed. Storage change s_{elec} depends on the imbalance between the total production $P_{\text{elec,tot}}$ and the total consumption $D_{\text{elec,tot}}(t)$ that includes not only the end-use consumption, but also the consumption by the electricity-consuming P2X technologies E2T and P2G. Charging is limited in both ends, the maximum being the available "space" in the storage $S_{\text{elec,max}} - S_{\text{elec}}(t-1)$ and the minimum being $\eta_{\text{sto,elec}} \cdot S_{\text{elec}}(t-1)$ to avoid storage depletion under 0. Assuming that the electricity storage is in use, the logic is

$$
\begin{aligned}
&\text{if } (P_{\text{elec,tot}}(t) > D_{\text{elec,tot}}(t)) \\
&\qquad s_{\text{elec}}(t) = \min\{P_{\text{elec,tot}}(t) - D_{\text{elec,tot}}(t); S_{\text{elec,max}} - S_{\text{elec}}(t-1)\} \\
&\text{else} \\
&\qquad s_{\text{elec}}(t) = -\min\{D_{\text{elec,tot}}(t) - P_{\text{elec,tot}}(t); \eta_{\text{sto,elec}} \cdot S_{\text{elec}}(t-1)\}
\end{aligned}
\tag{3.6}
$$

The second approach includes price-dependent storage operation. Electricity is exported when the price is high enough, instead of charging the storage, or imported when the price is low, instead of using stored electricity. The cut-off price which sets this price boundary is labelled $C_{\text{cut-off}}$, and the current Elspot electricity price is $C_{\text{Elspot}}(t)$ [56]. The cut-off price is set manually. This approach is not used in this study, but possibly in later studies.

$$
\begin{aligned}
&\text{if } (P_{\text{elec,tot}}(t) > D_{\text{elec,tot}}(t)) \\
&\qquad \text{if } (C_{\text{Elspot}}(t) > C_{\text{cut-off}}) \\
&\qquad\qquad s_{\text{elec}}(t) = 0 \\
&\qquad \text{else} \\
&\qquad\qquad s_{\text{elec}}(t) = \min\{P_{\text{elec,tot}}(t) - D_{\text{elec,tot}}(t); S_{\text{elec,max}} - S_{\text{elec}}(t-1)\} \\
&\text{else} \\
&\qquad \text{if } (C_{\text{Elspot}}(t) > C_{\text{cut-off}}) \\
&\qquad\qquad s_{\text{elec}}(t) = -\min\{D_{\text{elec,tot}}(t) - P_{\text{elec,tot}}(t); \eta_{\text{sto,elec}} \cdot S_{\text{elec}}(t-1)\} \\
&\qquad \text{else} \\
&\qquad\qquad s_{\text{elec}}(t) = 0
\end{aligned}
\tag{3.7}
$$

In both cases, if the electricity storage is not in use, $s_{\mathrm{elec}}(t)$ is naturally 0. The storage level changes with the same logic as in the heat case, shown in Eq. 3.5, with $\eta_{\mathrm{sto,elec}}$ affecting the discharge and $S_{\mathrm{elec,max}}$ being the user-defined maximum capacity of electricity storage.

Electricity import/export is calculated only after storage operation:

$$Import(t) = D_{\mathrm{elec,tot}}(t) - P_{\mathrm{elec,tot}}(t) + s_{\mathrm{elec}}(t), \tag{3.8}$$

where positive import implies electricity import to Finland, and negative import implies electricity export. Exchange capacities, shown in Table 3.7, are not included in the formula, but exceeding the capacities will result in an error notification.

3.3.3 Transport fuels

It is assumed that transport can utilize two kinds of fuel: oil and biofuel. In addition, according to the Finnish energy balance sheet [16], transport also consumes a small amount of electricity, but this consumption remains unaltered in the model. Although electric vehicles could provide a moving energy storage service, especially useful in large-scale integration of variable renewable energy [38], electric vehicles as such are excluded from this model, but they could be incorporated as an electricity storage capacity increase.

The model assumes that the transport sector has a priority over oil, i.e. if oil is available, it will be used as transport fuel. The amount of oil used in transport $P_{\mathrm{o.f.tr.}}$ in the simplest case would be

$$P_{\mathrm{o.f.tr.}} = \min \left\{ P_{\mathrm{un.o.}}; D_{\mathrm{tr.fuel}} \right\}, \tag{3.9}$$

where $P_{\mathrm{un.o.}}$ is the unconverted oil available in the fuel pool and $D_{\mathrm{tr.\ fuel}}$ is the transport fuel demand. However, the model allows pre-defining the amount of lignocellulosic biofuel manually, in which case the equation becomes

$$P_{\mathrm{o.f.tr.}} = \min \left\{ P_{\mathrm{un.o.}}; D_{\mathrm{tr.fuel}} - P_{\mathrm{man.bf.}} \right\}, \tag{3.10}$$

with $P_{\mathrm{man.bf.}}$ as the manually set amount of biofuel. This modification allows overriding the rule-based biofuel conversion, which is discussed in the next section, and directing the oil for other purposes, as an abundance of oil would have led to non-existent biofuel conversion.

The rest of the transport fuel demand $D_{\mathrm{tr.fuel}}$ will be filled by the rule-based biofuel conversion, that is produced by biomass conversion and/or P2L. The preference order between these two technologies is manually set by the user, which determines the formulas to be used. The missing transport fuel demand, after oil and the manually added biofuel, is first tried to be filled by the first preference, and then by the second. In the case of low oil, biomass and gas supply, it is possible that transport fuel demand is not met.

$$P_{\text{init}} = P_{\text{oil}} + P_{\text{man.bf.}} \tag{3.11}$$

$$
\begin{aligned}
&\text{if (biofuel conversion is preferred)}\\
&\quad \text{if } (P_{\text{init}} < D_{\text{tr.fuel}})\\
&\qquad In_{\text{bio}} = \min\left\{\frac{D_{\text{tr.fuel}} - P_{\text{oil}}}{\eta_{\text{bio}}}; P_{\text{b.a.}}\right\}\\
&\qquad Out_{\text{bio}} = \eta_{\text{bio}} \cdot In_{\text{bio}}\\
&\quad \text{if } (P_{\text{init}} + Out_{\text{bio}} < D_{\text{tr.fuel}})\\
&\qquad In_{\text{P2L}} = \min\left\{\frac{D_{\text{tr.fuel}} - P_{\text{oil}} - Out_{\text{bio}}}{\eta_{\text{P2L}}}; P_{\text{g.a.}}\right\}\\
&\qquad Out_{\text{P2L}} = \eta_{\text{P2L}} \cdot In_{\text{P2L}}\\
&\\
&\text{if (P2L conversion is preferred)}\\
&\quad \text{if } (P_{\text{init}} < D_{\text{tr.fuel}})\\
&\qquad In_{\text{P2L}} = \min\left\{\frac{D_{\text{tr.fuel}} - P_{\text{oil}}}{\eta_{\text{P2L}}}; P_{\text{g.a.}}\right\}\\
&\qquad Out_{\text{P2L}} = \eta_{\text{P2L}} \cdot In_{\text{P2L}}\\
&\quad \text{if } (P_{\text{init}} + Out_{\text{P2L}} < D_{\text{tr.fuel}})\\
&\qquad In_{\text{bio}} = \min\left\{\frac{D_{\text{tr.fuel}} - P_{\text{oil}} - Out_{\text{P2L}}}{\eta_{\text{bio}}}; P_{\text{b.a.}}\right\}\\
&\qquad Out_{\text{bio}} = \eta_{\text{bio}} \cdot In_{\text{bio}},
\end{aligned}
$$

where *In* and *Out* refer to energy input and output of a particular method, η to conversion efficiency, and subscripts "bio" and "P2L" refer to biomass conversion and P2L, respectively. $D_{\text{tr.fuel}}$ refers to transport fuel demand, P_{init} to the initially available fuel i.e. unconverted oil and manually added biofuel, $P_{\text{b.a.}}$ to unconverted biomass supply after the exclusion of must-run biomass, and $P_{\text{g.a.}}$ to gas supply, including both unconverted primary energy gas and the possible gas produced by P2G. What was excluded from the pseudo-codes above but was present in the actual codes, were the self-evident conditions: if the transport fuel demand was filled or the particular technology was disabled from the module structure, the input and output of the method would be zero.

As shown in the treatment of $P_{\text{b.a.}}$, the model aims to ensure that the biomass demand of process industry is met. The unconverted biomass supply after the conventional conversion methods is first used by the process industry, then by transport and only after then by the rest of the sectors, meaning mainly non-process industry. The biomass that is used as must-run biomass is calculated as

$$P_{\text{b.must.}} = \min\left\{P_{\text{un.b.}}; D_{\text{b.must.}}\right\}, \tag{3.12}$$

where $P_{\text{un.b.}}$ is the biomass left unconverted after the conventional conversion stage and $D_{\text{b.must.}}$ is the must-run biomass demand.

3.3.4 Advanced heat production

In the case that the heat demand is not met by the conventional sources (CHP, residential heat production etc.), there are four ways to fill the demand: E2T, P2G, additional separate heat production from fuels and heat storage. The preference order of these methods is defined by the user. Although P2G is mostly a production method from electricity to synthetic gas, the Sabatier process (2.2) produces high-exergy heat that could be utilized in district heating. The model is able to explore this possibility, but it is not included in the scope of this study.

For each timestep, the required heat demand D_{heat} after the conventional sources with static production profiles was calculated. After each method j, the remaining demand D^{j+1}_{heat} is calculated again until all four methods are taken into account. The operation of each method is based on the specific demand that is associated with it by the preference order, i.e. if for example E2T was the second preference, the heat demand that would define the E2T production would be the remaining demand after utilising the first preference. In the operation codes, this order-dependent demand to be filled is referred to as D^{j}_{heat}. Only after all the various production methods, the heat storage change $s_{\text{heat}}(t)$ is calculated based on $P_{\text{heat,tot}}(t)$ (see (3.4)-(3.5)).

Most of the four methods have boundary conditions that limit their operation. E2T is limited by the available overproduction of electricity, but this limitation can be changed to allow using also stored or imported electricity for E2T. P2G is limited by either the available electricity overproduction, heat demand or fuel demand, the choice being set by the user. The heat storage usage is naturally limited by the available stored energy. However, the additional separate heat production is not limited by the available fuel, as it is assumed to act as the last resort in the balancing of heat production. It was noticed that the hourly profiles of the conventional production and the heat demand were so mismatched that the heat storage and some additional heat production had to be included to balance the reference scenario without any P2X.

The pseudo-codes implementing the above-mentioned rules are:

E2T

$$
\begin{aligned}
&\text{if (E2T is in use and } D^j_{\text{heat}}(t) > 0) \\
&\quad \text{if (E2T is limited by overproduction)} \\
&\qquad P_{\text{E2T,heat}}(t) = \min\left\{D^j_{\text{heat}}(t); \eta_{\text{E2T}} \cdot P_{\text{elec,extra}}(t)\right\} \\
&\quad \text{elseif (E2T is limited by overproduction and storage)} \\
&\qquad P_{\text{E2T,heat}}(t) = \min\left\{D^j_{\text{heat}}(t); \eta_{\text{E2T}} \cdot (P_{\text{elec,extra}}(t) + \eta_{\text{sto,elec}} \cdot S_{\text{elec}}(t-1))\right\} \\
&\quad \text{else} \\
&\qquad P_{\text{E2T,heat}}(t) = D^j_{\text{heat}}(t) \\
&\text{else} \\
&\quad P_{\text{E2T,heat}}(t) = 0 \\
&D_{\text{E2T,elec}}(t) = \eta_{\text{E2T}} \cdot P_{\text{E2T,heat}} \\
&D^{j+1}_{\text{heat}}(t) = D^j_{\text{heat}}(t) - P_{\text{E2T,heat}}(t)
\end{aligned}
\tag{3.13}
$$

$P_{\text{E2T,heat}}$ refers to the heat produced by E2T and $D_{\text{E2T,elec}}(t)$ to the electricity consumed by E2T. $P_{\text{elec,extra}}$ refers to the electricity overproduction available for E2T, and $\eta_{\text{sto,elec}} \cdot S_{\text{elec}}(t-1)$ to the available stored electricity. Depending on the preference order between E2T and P2G, the available overproduction may be with or without the electricity consumption of P2G. D^{j+1}_{heat} refers to the remaining heat demand to be utilized by the method right after E2T.

As seen from the codes, E2T operation can be limited by electricity overproduction, storage or nothing. Electricity storage operates only after E2T, taking into account E2T's electricity consumption, according to the logic described in 3.3.2.

It should be noted that this E2T strategy does not allow converting electricity into heat beforehand, i.e. using E2T to charge the heat storage. The E2T operation is based on the current heat demand, and future heat demands are not foreseen. Additionally, the residential E2T is separated from the large-scale E2T. The additional RES-E2T aims to fill the missing residential heat demand, and it does not have any constraints.

Heat storage discharge

$$
D^{j+1}_{\text{heat}}(t) = D^j_{\text{heat}}(t) - \eta_{\text{sto,heat}} \cdot S_{\text{heat}}(t-1), \tag{3.14}
$$

where $\eta_{\text{sto,heat}} \cdot S_{\text{heat}}(t-1)$ is the available stored heat (see (3.4)). All available stored heat is always used. If the resulting $D^{j+1}_{\text{heat}}(t)$ is negative, methods after heat storage do not produce more heat. Additionally, the heat storage codes (3.4)-(3.5) ensure that the storage is not depleted under zero, but only the required heat is discharged from the storage.

Additional separate heat production

$$
\begin{aligned}
P_{\text{a.s.heat}}(t) &= \max\left\{D^{j}_{\text{heat}}(t); 0\right\} \\
D^{j+1}_{\text{heat}}(t) &= D^{j}_{\text{heat}}(t) - P_{\text{a.s.heat}}(t)
\end{aligned}
\tag{3.15}
$$

The only limitation for the additional separate heat production $P_{\text{a.s.heat}}$ is to be positive. This means that even in the reference scenario, some additional fuel has to be added to account for the additional separate heat production. However, in the reference scenario, the amount of added fuel is negligible.

P2G

In the case of P2G, the user can define for which purpose P2G is used: meeting the heat demand, meeting the fuel demand or consuming the overproduction of electricity. The aim of one final energy form is fulfilled, but at the expense that the constraints of the two other forms may be broken.

If the P2G priority is **electricity**, the formulas are

$$
\begin{aligned}
D_{\text{P2G,elec}}(t) &= P_{\text{elec,extra}}(t) \\
P_{\text{P2G,heat}}(t) &= \eta_{\text{P2G,heat}} \cdot D_{\text{P2G,elec}} \\
P_{\text{fuel}} &= \eta_{\text{P2G,gas}} \cdot \sum_{t} D_{\text{P2G,elec}}(t),
\end{aligned}
\tag{3.16}
$$

where $D_{\text{P2G,elec}}$ is the electricity consumed by P2G, $P_{\text{P2G,heat}}$ the heat produced by P2G and P_{fuel} the synthetic gas produced by P2G. As along to the principles of the model, the electricity and heat are calculated on an hourly basis, whereas fuel is calculated only as an annual sum. The conversion efficiencies $\eta_{\text{P2G,heat}}$ and $\eta_{\text{P2G,gas}}$ refer to the conversion from electricity to the indicated product. If there is more electricity overproduction that would be needed to fill the fuel demand, P2G stops operating when the fuel demand is met.

If the P2G priority is **heat**, the formulas are

$$
\begin{aligned}
D_{\text{P2G,elec}}(t) &= \frac{P_{\text{P2G,heat}}(t)}{\eta_{\text{P2G,heat}}} \\
P_{\text{P2G,heat}}(t) &= D^{j}_{\text{heat}}(t) \\
P_{\text{fuel}} &= \eta_{\text{P2G,gas}} \cdot \sum_{t} D_{\text{P2G,elec}}(t)
\end{aligned}
\tag{3.17}
$$

It should be noted that the heat preference order and the P2G order are separate. If P2G is the first preference to fulfil the heat demand and heat was selected as the P2G priority, all the remaining heat demand would be met with P2G, possibly resulting in major electricity import or an excess of fuel, as there would be no limitations to P2G operation. If electricity or fuel is selected as P2G priority, there will be a boundary for P2G operation.

If the the P2G priority is **fuel**, the formulas are slightly more complicated. The fuel demand that would be met by P2G is

$$
\begin{aligned}
D_{\text{P2G,fuel}} &= D_{\text{ind.fuel}} + D_{\text{gas,P2L}} \\
&\quad - \left(\sum_{\text{fuel pool}} P - D_{\text{b.must.}} - D_{\text{o.f.tr.}} - D_{\text{fuel,a.s.heat}} - D_{\text{b.}} \right)
\end{aligned} \tag{3.18}
$$

$D_{\text{ind.fuel}}$ and $D_{\text{gas,P2L}}$ refer to industrial fuel demand and gas demand for P2L, respectively, and they form the total demand of fuel. The remaining terms form the existing supply of fuel. $\sum_{\text{fuel pool}} P$ is the sum of all the unconverted fuels in the fuel pool after the conventional conversion, $D_{\text{b.must.}}$ the amount of biomass used as must-run biomass (Eq. (3.12)) and $D_{\text{o.f.tr.}}$ is the amount of oil used in transport (Eq. (3.9)). $D_{\text{fuel,a.s.heat}}$ is the fuel demand of additional separate heat production, included only if additional separate heat is preferred to P2G, and $D_{\text{b.}}$ is the biomass demand of the biofuel conversion, included only if biofuel conversion is preferred to P2L. Additionally, P2L gas demand $D_{\text{gas,P2L}}$ depends on the preference order between biomass conversion and P2L:

$$
\begin{aligned}
&\text{if (biofuel conversion is preferred)} \\
&\quad D_{\text{gas,P2L}} = \frac{D_{\text{tr.fuel}} - P_{\text{oil}} - Out_{\text{bio}}}{\eta_{\text{P2L}}} \\
&\text{if (P2L conversion is preferred)} \\
&\quad D_{\text{gas,P2L}} = \frac{D_{\text{tr.fuel}} - P_{\text{oil}}}{\eta_{\text{P2L}}},
\end{aligned} \tag{3.19}
$$

where $D_{\text{tr.fuel}}$ refers to transport fuel demand, P_{oil} to oil available as unconverted primary energy, Out_{bio} to biofuel output from biofuel conversion and η_{P2L} to the conversion efficiency of P2L (Eq. (3.11)).

After having set the fuel demand for P2G, the formulas are

$$
\begin{aligned}
D_{\text{P2G,elec}}(t) &= \frac{P_{\text{fuel}}}{\eta_{\text{P2G,gas}} \cdot 8760\ \text{h}} \\
P_{\text{P2G,heat}}(t) &= \frac{\eta_{\text{P2G,heat}} \cdot D_{\text{P2G,elec}}}{8760\ \text{h}} \\
P_{\text{fuel}} &= D_{\text{P2G,fuel}}
\end{aligned} \tag{3.20}
$$

Since in this case there is no existing hourly profile for P2G, the profile was assumed to be flat.

Finally, as with all the other heat production methods, the remaining heat demand after P2G is in all the cases

$$
D^{j+1}_{\text{heat}}(t) = D^{j}_{\text{heat}}(t) - P_{\text{P2G,heat}}(t). \tag{3.21}
$$

Even though the model includes the possibility of using P2G in heat production, the option can also be disabled. In that case, heat production is skipped from the codes, and P2G is a direct conversion from electricity to fuel. However, the priority between electricity and fuel still determines whether P2G is constrained by electricity overproduction or not.

3.4 Limitations of the model

Operating mostly on the macro level, the model has several limitations and restricting assumptions. These limitations are acknowledged, and a fully-detailed simulation of the Finnish energy system was considered to be outside the scope of this thesis. This section will describe the most important assumptions.

Firstly, one of the assumptions that deviate from reality the most is the treatment of hourly electricity production data. As described previously, the hourly data is simply scaled from the historical production data. In reality, the power plants are operated based on actual load and demand and the cost of generating the electricity in the available power plants, i.e. merit order. However, the simulation that would be required for extensive hourly-level production calculations is outside the scope of the model, and an approximate, but realistic hourly production data was considered to be representative enough for the purposes of the model. The purpose is not to simulate the operation of the whole energy system, but to test out the feasibility of future scenarios in a semi-realistic way. The model should not be used as a detailed reference for hourly production.

The second-most significant assumption is the exclusion of transmission and system requirements. All transmission within Finland was assumed to be unrestricted, and the system requirements such as the ramping levels of individual power plants are not taken into account in the model. Additionally, the costs of the grid and transmission are not included. The reason for this simplification is again the required extensive simulation on power plant and grid level, which was considered to be too detailed for the purposes of the model.

There are also some assumptions on the weather-related input data that are worth noticing. Firstly, the model is using the temperature data of only one weather station, namely Jyväskylä Airport, as an approximation of the whole country's temperature. This type of an approximation is common, and Central Finland is used in at least one study [3].

Secondly, the wind and solar power distribution does not consider the spatial variance of wind and solar resources in Finland. In the case of wind power, the capacity distribution is assumed to be similar to actual distribution in the reference year, i.e. new sites for onshore or offshore wind power are not taken into account. However, since the model uses the wind power production of the whole Finland, spatial and temporal variation is already smoothed and the scaled hourly wind power production should reflect on the real situation and wind resources.

In the case of solar power, the used data is scaled from the production data of a 1 kW_p solar panel located in Helsinki, causing the solar production data to be significantly less distributed than wind data. However, the Finnish solar resources do not have large spatial variation. The yearly global irradiation in Finland excluding the northernmost Lapland is approximately 1000-1150 kWh/m^2, corresponding to about 800-1000 kWh/kW$_p$ [59]. In the Helsinki panel data, the yearly total 980 kWh/kW$_p$ falls on the upper end of the range, and the data can be used to represent the solar irradiance in Southern Finland, where the majority of city-based solar power is assumed to be located.

Lastly, there are some assumptions regarding the model structure and operational modules. For example, we assume that transport sector can only utilize oil, biofuel and, to some extent, electricity as fuel. In reality, transport sector can also use natural or synthetic gas. Especially biogas utilization could be paramount in transport decarbonisation. However, we assume that the transport sector does not change significantly, and electric and biogas-consuming vehicles are not included in the model.

One of the other simplifications in the implementation is the lack of temporal loss in storage. The model assumes that the only loss from energy storages is the overall round-trip efficiency that includes the losses due to charging and discharging. The storages cause no constant losses, which is only for the sake of simplicity. Since in the model, the storage levels usually tend not to stay high for an extended time period, we assume that the lack of temporal loss is not an issue. In a similar fashion, the losses in the electricity and district heating grids are not explicitly calculated, but they are included as consumption.

As for the operational and functional side of the model, the only fully-automated part of the model is the rule-based operation of the advanced conversion methods and storages. The amounts of primary energy sources and their allocation between conventional conversion methods has to be done manually by the user. In principle, one could be able to optimize the primary energy sources and their allocation by minimizing the resulting costs, but the computing power of Excel's Solver, however, is too low to smoothly manage a process this complicated. Therefore, building the production scenarios is done mostly manually, and it might be a time-consuming process. On the other hand, the scenarios can be built with great freedom.

Chapter 4

Scenarios

This chapter will focus on describing the different scenarios tested out with the model, and the results of the scenarios are presented in Chapter 5. The future scenarios the thesis will explore are presented for the years 2013, 2030 and 2050. The original 2013 scenario used as a reference for all the other scenarios is presented first.

4.1 Reference scenario

The reference scenario of the model is the realistic case of Finland in 2013, based on the 2013 energy balance sheet from Statistics Finland [16]. This scenario will be used as reference for various system modifications, and the model itself builds upon this original scenario.

The main parameters of the 2013 reference scenario are listed in Tables 4.1, 4.2 and B.1. In short, the reference scenario follows the 2013 energy balance sheet. The only deviation from the official balance is the fuel for additional separate heat production required to balance the hourly heat production. This fuel amount is insignificantly small, 282 TJ, compared to the total primary energy input, and it is assumed to be composed of natural gas. Being a reference scenario, no advanced P2X technologies are included, and only heat storage is in operation. The only P2X method included is the existing residential E2T.

In the reference scenario, 46 % of the total primary energy is from fossil sources, 19 % nuclear, 31 % renewable and 5 % from other sources. In electricity production, the share of renewables is 31 % and in heat production 45 %. In the model, oil, coal, peat and natural gas are considered fossil sources, and hydropower, biomass, waste-to-energy, wind, solar and heat pumps are considered renewable. Nuclear forms its own category, and the other sources are electricity import and the "others" category.

The cost of the reference scenario is calculated according to the cost assumptions made in section 3.2.4. The total annual cost was calculated to be 8 billion euros, and the more detailed breakdown is shown in Table 4.3. The total investment cost of the plants was calculated to be 29 billion euros.

It should be noted that these numbers might not reflect on the actual costs of the whole Finnish energy system. The cost calculations do not include for example transmission costs or taxes. However, they can be used as a reference when comparing

Table 4.1: Primary energy input in the reference scenario. Almost identical to the original 2013 energy balance sheet from Statistics Finland [16], with the exception of natural gas. Additional 282 TJ of natural gas has been added to account for the additional separate heat production required to balance the hourly heat production.

Primary energy source	Amount	Unit
Oil	334 976	TJ
Coal	134 829	TJ
Natural gas	107 327	TJ
Peat	56 892	TJ
Nuclear	257 520	TJ
Hydro	46 238	TJ
Biomass	352 042	TJ
Waste-to-energy	4 434	TJ
Wind	2 786	TJ
Solar PV	0	TJ
Solar thermal	0	TJ
Others	5 428	TJ
Heat pumps	4.6	TWh
Electricity import	15.7	TWh

Table 4.2: Consumption in the reference scenario, based on the 2013 energy balance sheet [16]. The electricity consumption 68.9 TWh refers to the final energy demand used as electricity, excluding the part used for residential electric heating, listed as heat demand. The total electricity demand in 2013 was 84.0 TWh, which is also the sum of electricity production and import.

Sector	Final energy type				
	Electricity TWh	Heat TWh	Industrial fuel TJ	Must-run biomass TJ	Transport fuel TJ
Process industry	33.7	13.1	117 345	134 350	-
Other industry	6.5	4.2	27 050	-	-
Transport	0.7	-	-	-	211 448
Residential	9.8	50.3	-	-	-
Public sector	15.6	18.9	-	-	-
Transmission losses	2.6	3.7	-	-	-
Total	68.9	90.3	144 395	134 350	211 448

Table 4.3: The cost breakdown of the reference scenario.

Type	Cost (M€)
Annualized investment	758
Annual O&M	578
Fuel cost	5 655
Electricity import	651
Emission costs	408
Total annual cost	8 050
Total investment	28 955

the costs of future scenarios. In the model, we focus on the relative cost difference, rather than the absolute costs. For calibration, we can compare the available actual costs and the respective output from the model. The Finnish expenditure on energy import was 7.8 billion euros in 2011 [60], whereas the cost assumptions of this study result in a total import cost of 5.1 billion euros, so we can quite safely state that the costs are within the same order of magnitude. The difference might be due to the exclusion of taxes or the fact that the model uses the fuel costs for a different year.

The 2013 reference scenario is visualized in Fig. 4.1 as a Sankey diagram. In the Sankey diagram, the widths of the energy flows are proportional to the flow quantity. A more detailed diagram can be found in Appendix C in Fig. C.1, including also the energy flow quantities in TJ.

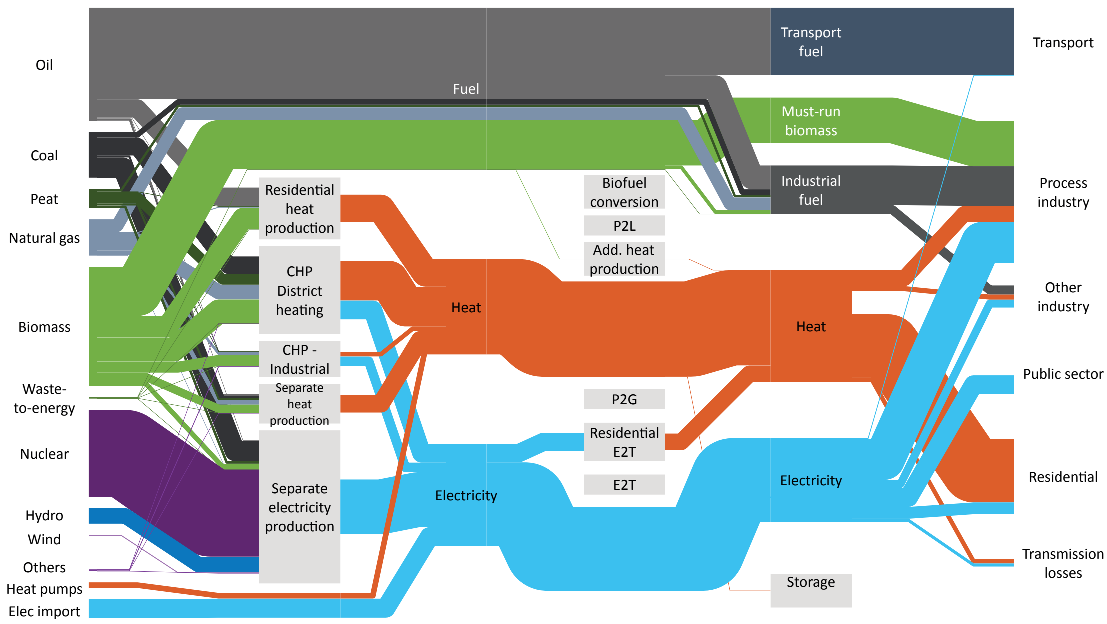


Figure 4.1: The 2013 reference scenario visualized as an energy flow. A larger and more detailed visualization can be found in Appendix C in Fig. C.1, including also the energy flow quantities in TJ.

4.2 Cost projections

All costs related to energy systems will change over time: fuel, technology and emission costs. However, for simplicity, in this thesis we assume that only the costs of wind power, solar PV and electricity storage vary over time, since their cost evolution will be the much more rapid and pronounced than for example the cost of conventional power plants. We also assume that the carbon price will increase over time (see Table 3.6).

The cost projections according to the IEA Technology Roadmaps, that used in the scenarios, are listed in Table 4.4. It is assumed that the O&M costs change at the same rate as the investment costs. The cost of wind power is assumed to drop by -12 % by 2030 and -18 % by 2050. For solar PV, the cost projections are -50 % and -63 %, respectively, and for electricity storage, -42 % and -84 %. Carbon price is assumed to increase significantly, +65 % by 2030 and +1200 % by 2050.

All the other costs are assumed to remain on the 2013 level, listed in Tables 3.4-3.3.

Table 4.4: Cost projections for the years 2030 and 2050. In this thesis, it is assumed that only the costs of wind power, solar PV and electricity storage, as well as carbon prices, vary over time. All the costs not listed here will remain in the 2013 level (see Tables 3.4-3.3).

Technology	Cost	Unit	2013	2030	2050	Source
Wind power	Change from 2013			-12 %	-18 %	[61]
	Inv. cost	€/kW_e	1 386	1 223	1 142	
	Fixed O&M	€/kW_e	37	33	30	
	Variable O&M	€/MWh	11.0	9.7	9.1	
Solar PV	Change from 2013			-50 %	-63 %	[62]
	Inv. cost	€/kW_e	1 538	769	566	
	Fixed O&M	€/kW_e	17	8	6	
	Variable O&M	€/MWh	8.2	4.1	3.0	
Electricity storage	Change from 2013			-42 %	-84 %	[63]
	Capacity cost	€/MWh	1 000	580	160	
	Power cost	€/MW	500 000	290 000	80 000	
	Annual O&M	% of inv.	3 %	3 %	3 %	
Carbon price		€/tCO_2	8	60	105	[1]

4.3 Consumption scenarios

In this thesis, two different scenarios for consumption are addressed: "high" and "low". The "high" scenario is based on the 2013 National Energy and Climate Strategy by the Ministry of Employment and the Economy [31]. The "low" scenario is based on one of the scenarios presented in VTT's Low Carbon Finland 2050 Platform report [33], the "Säästö" scenario to be precise, and it had the lowest energy consumption in 2050. Both of these scenarios were originally provided with a production and consumption scenarios, but for the purposes of this thesis, only consumption scenarios were considered. This thesis uses existing scenarios, instead of estimations of own making, in order to have realistic scenarios. Both of these scenarios are based on an extensive collection of background data and assumptions, regarding for example building stock, demographics and national economy developments, the scope of which would have been beyond this thesis.

The "high" scenario assumes that the energy and environmental policies are frozen on the 2013 level, and its purpose was to evaluate the effects of the current policies on future developments. Therefore, the "high" scenario can be considered as the business-as-usual in consumption. In general, the "high" scenario assumes that national economy will grow and energy demand will increase across all sectors except for transport and space heating. Especially electricity consumption will increase in most sectors. Heat demand will decrease due to tightening building regulations and the lower heat demand of new buildings, and space heating with oil and electric boilers will decrease as heat pumps become more common. Transport volumes will increase notably, but the technological development causes the transport fuel consumption to decrease slightly.

The "low" scenario takes the opposite approach. Fast greenhouse gas emission reductions are paramount in EU policies, and energy savings are pursued at any cost. International trade and thus Finnish export will decrease, and energy self-sufficiency is emphasized. The energy efficiency of buildings will increase, and the share of district heating and fuels in space heating will decrease. Consumption patterns and consumer values will become more sustainable, and energy efficiency and smart use of resources are valued. Public transport will become more important, reducing the transport fuel demand. The current social and industrial structure will remain largely unchanged, and technological development is conservative. Industrial energy demand will decline due to energy efficiency measures. However, electricity demand will rise in all sectors except for process industry.

The two scenarios have some similar trends: electricity demand will increase, and heat demand and transport fuel demand will decrease. In addition, electric vehicles will gain popularity, and space heating will shift from fuel and electric boilers to heat pumps. However, in terms of final energy demand and industrial demand, the two scenarios differ significantly. In the high scenario, the final energy demand will increase +3 % from the 2013 level by 2030 and +9 % by 2050, whereas in the low scenario the respective changes are -13 % and -16 %. Figure 4.2 highlights two indicators of the scenarios: final energy and electricity consumption, presented together with historical data from Statistics Finland. Figure 4.3 illustrates the

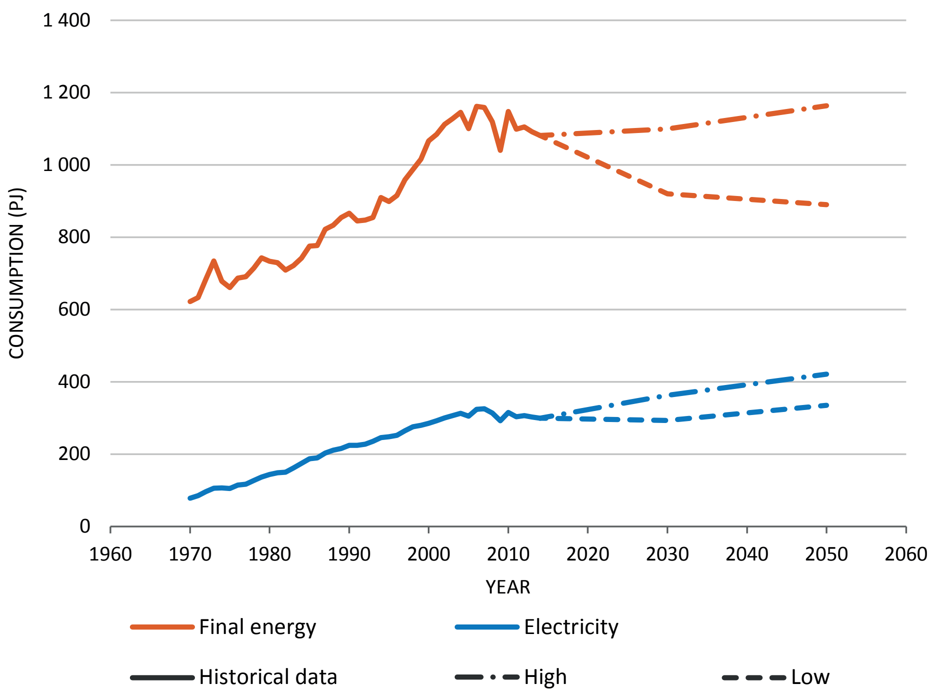


Figure 4.2: The final energy and electricity consumption in the two consumption scenarios, illustrated with historical data [2]. The solid line refers to historical data, dot-dash to the "high" scenario, and dashed to the "low" scenario.

consumption by sector and by energy type in each case, and the detailed numerical data of the consumption scenarios can be found in Table B.2.

The two scenarios were also chosen due to their opposite approaches. The high scenario serves as a business-as-usual consumption projection with continuously increasing consumption, which is a common assumption used in political discussion. On the other hand, the low scenario serves as the radical opposite scenario of decreasing demand, which is not typically considered as a possible future prospect. The two scenarios could be considered as the extremes of future consumption development. Therefore, it is most valuable to address both trends in the scope of this thesis, as the actual 2050 consumption is likely to be somewhere between these two extremes.

4.4 Production scenarios

In addition to the consumption scenarios, various different production scenarios are tested out with the model, which is the main purpose of the thesis. The aim is to formulate production portfolios that match the consumption, using the different blocks of the model. The production portfolios will consist of primary energy input, allocation between conventional conversion nodes, and P2X technology inclusion. The P2X nodes i.e. the advanced conversion functions automatically, but the allocation to conventional conversion is done manually. By changing the amount of different primary energy sources and their allocation, storage capacities and P2X

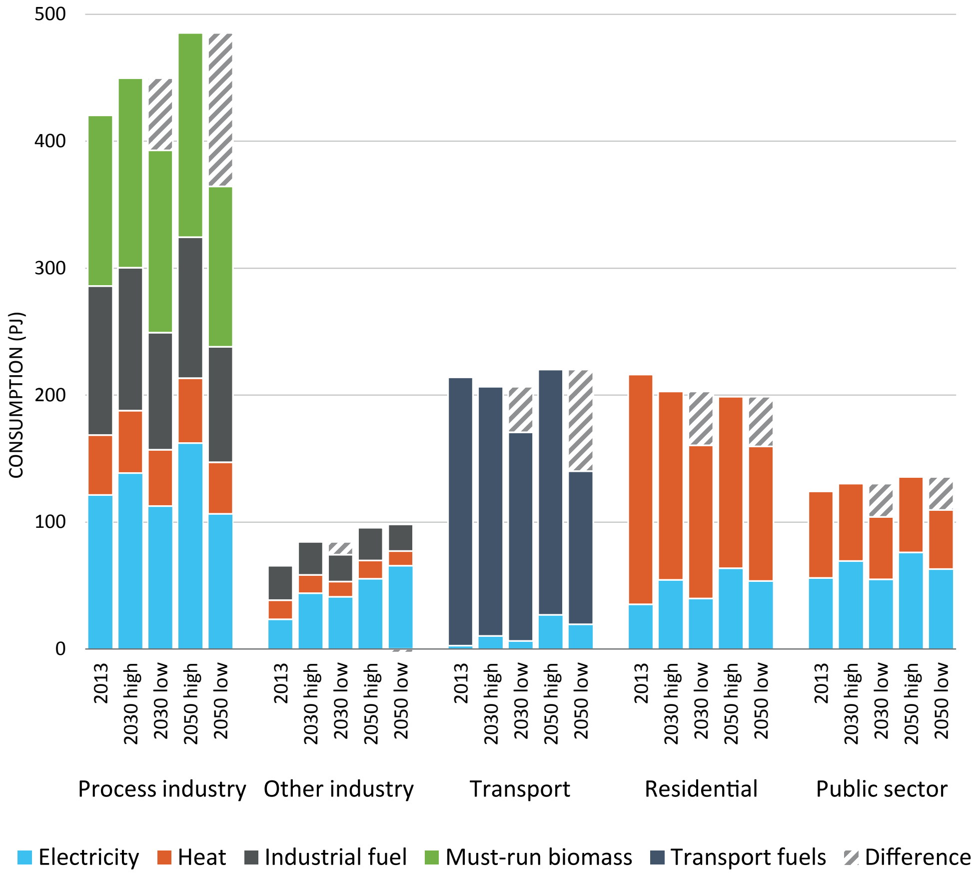


Figure 4.3: The consumption scenarios used in this thesis, presented graphically. The more detailed numerical data can be found in Appendix B in Table B.2. Each column groups illustrates one sector, and the five different columns represent the five cases: 2013 reference, and the "high" and "low" scenario for 2030 and 2050. The striped area illustrates the difference between the two consumption scenarios.

node inclusion, we will try to form consumption-matching production portfolios according to the scenario guidelines, described in the following subsections.

4.4.1 Business as usual

In the "Business as usual" scenario, also named BAU, the production portfolio will remain similar to the current production. The BAU scenario follows the basic scenario of the 2013 National Energy and Climate Strategy by the Ministry of Employment and the Economy [31], the same as the "high" consumption scenario. The strategy is only slightly modified to have a functioning scenario in the model.

Fossil fuels will still form a major part of the energy system, but the share of biomass and nuclear power will increase. Wind and especially solar power will not have a major role in electricity generation. P2G, P2L or electricity storage do not exist, but biofuel conversion and residential E2T are allowed. Wind power will not be added significantly: +3.6 GW by 2030 [31] and +4 GW by 2050, the 2013 level being 0.5 GW. The amount of hydropower and biomass will be increased moderately. The amount of biofuel used in tranport will rise to 22 000 TJ by 2030 and to 37 000 TJ by 2050, constituting 11-31 % of the fuel consumption in transport, depending on the year and the consumption scenario used. Biofuel amounts are based on the VTT report [33]. Solar power will not be added to the system in this scenario, and the 2013 storage capacities remain unchanged.

In 2013, there were four operational nuclear power plants in Finland: Loviisa 1 and 2, and Olkiluoto 1 and 2, and their combined nominal power is approximately 2750 MW. One additional power plant, Olkiluoto 3 with the nominal power of 1600 MW, is (as in 2015) under construction. Additionally, there is a pending application for Hanhikivi 1 (1200 MW), and until recently, for Olkiluoto 4 (1500 MW) [64]. We will assume that Loviisa 1 and 2 will be decommissioned before 2030, 2027 and 2030 being the extents of their operation permits [31], and Olkiluoto 1-4 as well as Hanhikivi 1 are in operation, and +500 MW capacity is acquired from technical upgrades. In 2030, the total available nuclear capacity is thus assumed to be 6560 MW, as stated in the TEM 2013 report [31]. By 2050, all existing capacity will have been decommissioned, but new additional capacity may have been built, and the total available capacity is assumed to be 6500 MW.

When building the BAU scenarios, the TEM 2013 report [31] is used as a starting point. Initial input values for primary energy are only slightly modified, and the power output from the conventional conversion (CHP etc.) is optimized by minimizing the heat loss. No cost optimization is used in the BAU scenarios. The relative amounts of fossil fuels and biomass are also based on the TEM report.

When adding new capacity to the system, it is assumed that the ratio between capacity and electricity production stays the same as in 2013.

4.4.2 Government programme

The third production scenario, labelled GOV, will address the feasibility of the current government programme [5]. The energy-related goals of the programme to be achieved before 2030 are

- Share of renewable energy over 50 %
- Self-sufficiency over 55 %
- Coal no longer be used in energy production
- Oil usage cut in half
- Share of renewable transport fuels to 40 %

In this scenario, the production portfolio will be biomass-heavy, and the amount of fossil fuels is cut significantly. All P2X modules are allowed. Since the programme does not list any goals for nuclear energy, it is assumed that the nuclear capacity is the same than in the BAU scenario. The main difference to the BAU scenario is the inclusion of P2X, cuts in fossil fuels and an increased focus on wind and solar power.

A more detailed optimization method is used to build to GOV scenarios. A heuristic multi-objective target function X for the optimization was composed, and it includes the objectives of annual cost (C_{annual}) minimization, maximization of self-sufficiency (α_{self}) and the share of renewables in primary energy consumption (α_{RES}) and storage loss (L_{heat} and L_{elec}, both < 0) minimization:

$$\min X = \frac{C_{\text{annual}}}{10^8} - 100\ \alpha_{\text{self}} - 100\ \alpha_{\text{RES}} - 100\ L_{\text{heat}} - 100\ L_{\text{elec}} \tag{4.1}$$

The objectives are scaled so that costs and shares are scaled to $\sim 10^2$ and the storage objectives to ~ 10. This kind of an objective function was found useful in defining the GOV scenarios. The variables used in the optimization are the amounts of primary energy excluding nuclear, coal (set to zero) and hydro power, storage capacities and allocation to conventional conversion. Additionally, the amount of oil in 2030 is set to be half of the 2013 amount, whereas in 2050 the amount of oil is a variable. The constraints include not exceeding the renewable potentials or exchange capacities, and that the error in the final energies should be less than 0.1 %. Due to the condition-based P2X rules, linear optimization cannot be used, and Excel's GRG (Generalized Reduced Gradient) Nonlinear Solving method is used to find a local minimum.

4.4.3 VRE addition

This scenario studies the role of P2X in variable renewable energy (VRE) integration, including wind power and solar PV. The aim is to find out how much wind and solar power can be technically added to the system by allowing different P2X technologies. The different P2X combinations tested out in this section are listed in Table 4.5. Contrary to the previous scenarios, additional residential E2T is disabled, and only the large-scale E2T is used in controlled VRE integration.

Table 4.5: The cases of the VRE addition study. The "X" refers to a P2X technology being allowed in the case.

	P2X included			
Case	Existing RES-E2T	E2T	P2G	Electricity storage
No P2X	X			
E2T	X	X		
P2G	X		X	
Sto	X			X
E2T+Sto	X	X		X
E2T+P2G	X	X	X	
P2G+Sto	X		X	X
E2T+P2G+Sto	X	X	X	X

The optimization is done by maximizing the level of VRE integration in the system, measured as the share in primary energy consumption, while also minimizing the storage capacities to avoid the misuse of storage to artificially increase the VRE share. The target function Y in this case is

$$\min Y = 100\ \alpha_{\mathrm{VRE}} - S_{\mathrm{heat,max}} - S_{\mathrm{elec,max}}, \tag{4.2}$$

where α_{VRE} is the share of VRE in primary energy consumption and $S_{\mathrm{heat,max}}$ and $S_{\mathrm{elec,max}}$ are the storage capacities required. The variables in the optimization are wind and solar power and the outputs from conventional conversion, excluding fuel-based residential heating, and the only system constraints are exchange capacities. For the cases including P2G, the amount of coal is also a variable, to act as a driver for P2G operation. The model automatically ensures that the final energy demands are met.

The primary energy input is slightly simplified in these calculations in order to run the optimization more smoothly. Conventional conversion is assumed to use only biomass as fuel, the industrial fuel demand is composed of only coal, and oil is used only in transport. The residential fuel-based heating, which remains unchanged, however still uses minor amounts of fossil fuel. These simplifications in primary energy input affect only emissions and costs, while the system operation is unaffected.

In this scenario, the potential for wind and solar are assumed to be infinite, with the purpose of studying the effect of P2X on the technical integration of VRE. Costs will not be taken into account in the optimization, and only the 2013 consumption scenario is considered. In addition, for the purpose of studying the absolute maximum integration, the maximum storage capacities are also assumed to be unconstrained. The required storage capacities will be included in the results.

Note that this scenario is a technical integration study. Since costs are not included in the optimization in any way, the resulting scenarios will most probably not be economically feasible. The results merely have to be seen as technical exploration.

4.4.4 Renewable energy potential

Since most production scenarios deal with renewable energy additions, it is important to take into account the limits in renewable energy potential. The limits of the Finnish renewable energy potential were also discussed in some studies [3, 33, 65], and the estimated potential limits in these studies are listed in Table 4.6. This thesis assumes the lowest reported potential, also included in the table. Two of the sources reported the gross potential of renewable sources, whereas one source reported the technical potential, explaining the difference between the reported potentials.

The hydropower potential is similar in all the sources, since the Finnish hydropower capacity is already rather fully exploited, leaving little possibility for additional capacity. As for wind power potential, the Finnish wind resources are theoretically limitless, but Zakeri et al. noted that 20 GW wind installations might occupy roughly 10 % of the country's onshore and offshore surface area [3]. As for solar PV, the theoretical capacity is also considered limitless, but 3 TWh/a is assumed to correspond 60 % roof coverage of all south-facing residential buildings in Finland [3], which gives some idea of the practical consequences of high solar capacity.

Table 4.6: Renewable energy potential in Finland according to various sources. This thesis assumes the lowest reported potential.

Energy source	Zakeri et al., 2015 [3]	VTT, 2014 [33]	Lund, 2007 [65]	This thesis	Unit
Biomass	515 000	480 000	470 000	470 000	TJ
Waste-to-energy	-	25 000	90 000	25 000	TJ
Hydro	60 000	58 000	58 000	58 000	TJ
Wind	∞	144 000	72 000	72 000	TJ
Solar PV	10 800	18 000	-	10 800	TJ
Solar thermal	5 400	-	2 000	2 000	TJ
Heat pumps	14	17	-	14	TWh
Type of potential	Gross	Gross	Technical	Technical	

4.4.5 Scenario building method

The building of a scenario always starts by determining the consumption as the model ultimately aims to balance the production and consumption in terms of consumption. After this, the primary energy, their allocation to conventional conversion and the inclusion of P2X technologies is done more or less manually. The P2X modules themselves are rule-based and thus, operate automatically to balance production and consumption, and the rules are discussed in 3.3. However, the amounts of conventional conversion can also be optimized in various ways. For example, in BAU scenarios the heat loss is minimized, whereas in GOV scenarios a more elaborate multi-objective target function is used.

Cost optimization can also be performed, but it is not the main function of the model. If needed, the amount of some primary energy sources can be cost-optimized if the fuel demand for CHP and separate production are known. However, the model's computing power has not been tested for a full cost-optimization, including all the primary energy sources and all the constraints. It is estimated that the model's computing power is not enough for a full optimization, as the model is not optimized for optimization. Excel's Solver does not find the global minimum, only a local one, and therefore the choice of initial values is important as it affects the end result.

More practical instructions about using the model are given in section A.2.

Chapter 5

Results

This section presents the outcomes of the model and the scenarios. All the available data is not presented here, and for example, hourly production data is not presented, and the results are discussed mostly in the annual level.

The scenarios discussed in this chapter are introduced in the previous chapter. The "high" consumption scenario is based on the 2013 National Energy and Climate Strategy by the Ministry of Employment and the Economy [31], and it acts as the business-as-usual scenario in consumption. The "low" scenario is based on one of the scenarios presented in Low Carbon Finland 2050 Platform report [33], and it takes the opposite approach as the "high" scenario. Fast greenhouse gas emission reductions are paramount in EU policies, and energy savings are pursued at any cost.

5.1 Comparison of BAU and government programme

The business-as-usual scenario (BAU) is a representation of the 2013 National Energy and Climate Strategy by the Ministry of Employment and the Economy [31], described in more detail in 4.4.1, whereas the government programme (GOV) follows the guidelines of the current government programme [5], the goals of which are listed in 4.4.2.

The results of the BAU and GOV scenarios are shown in Figs. 5.1-5.5 which show the annual primary energy consumption, production, annual costs and CO_2 emissions of the different scenarios. Additionally, the Sankey diagrams of all the BAU and GOV scenarios can be found in Appendix C.

In the BAU scenarios, the overall composition of the primary energy consumption remains similar to 2013, with the exception of nuclear power. Due to the upcoming nuclear power plants constructions, the share of nuclear energy in primary energy consumption and in electricity production increases considerably. In the "high" scenario, nuclear power will cover approximately 36 % of the primary energy consumption, 44 % in the "low" scenario, regardless of the year. In electricity production, the share of nuclear power is even higher, around 50 % in the "high" and almost 60 % in the "low" scenario. Since nuclear production profile is very flat compared to the varying electricity consumption, a large share of non-adjustable nuclear power puts considerable strain on the system.

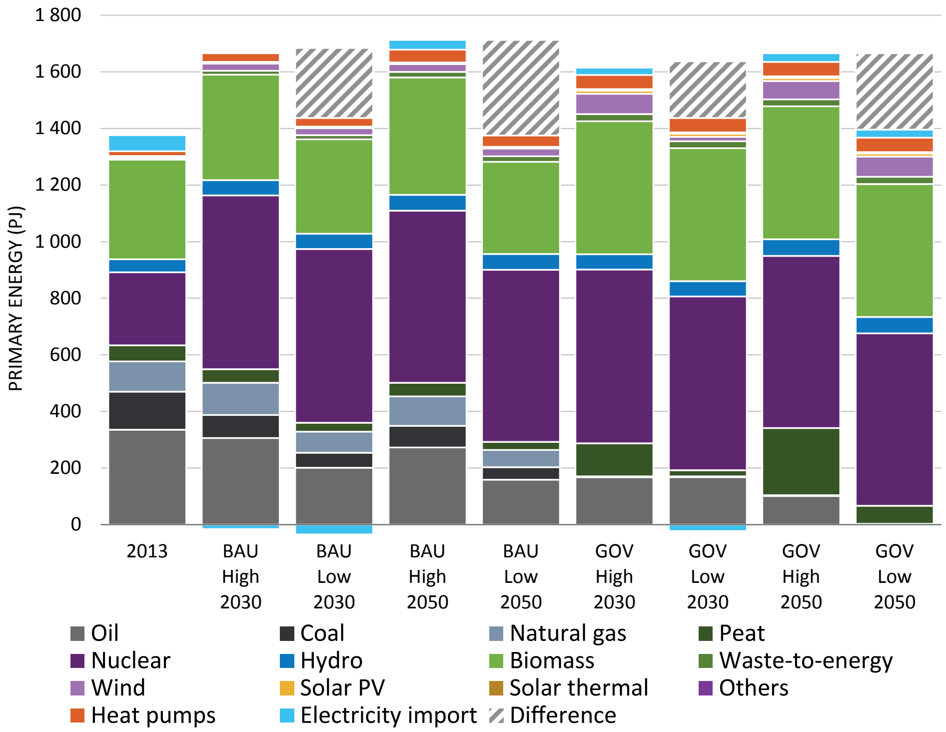


Figure 5.1: Primary energy consumption between 2013-2050 in the two scenarios. BAU refers to business-as-usual, and GOV to the government programme.

A high amount of nuclear base load also affects wind energy integration, especially due to the limited export capacities. It was discovered that the highest strain on export capacities occurred during Midsummer, when the electricity consumption was exceptionally low, producing a peak to the already low summer demand, while at the same time, wind energy production was peaking up. While this might be a peculiarity related to the year 2013, it demonstrates well the worst-case scenario of wind integration that should always be taken into account: low demand, high production and limited exchange capacities.

As seen in Fig. 5.2, in both consumption scenarios of BAU, Finland will be a net electricity exporter in 2030, whereas in 2050 Finland is again a net importer in the high scenario, and independent in the low scenario. The 2030 export is probably caused by the higher nuclear power, whereas the 2050 import can be explained by the increased electricity consumption. From Fig. 5.3 it can also be noticed that CHP will become less popular in all BAU scenarios, possibly due to the increased nuclear power, decreased heat demand and increased usage of heat pumps.

From the cost analysis in Fig. 5.4 and Table 5.1, we can see that the annual costs of the energy system increase in the "high" scenario and remain unchanged in the "low" scenario. The largest cost differences arise from fuel usage and the related CO_2 emission costs, as the "high" scenario utilizes higher amounts of fossil fuels. However, the total investment costs, found in Table 5.1a, increase significantly. Most of this increase is caused by the new nuclear plants.

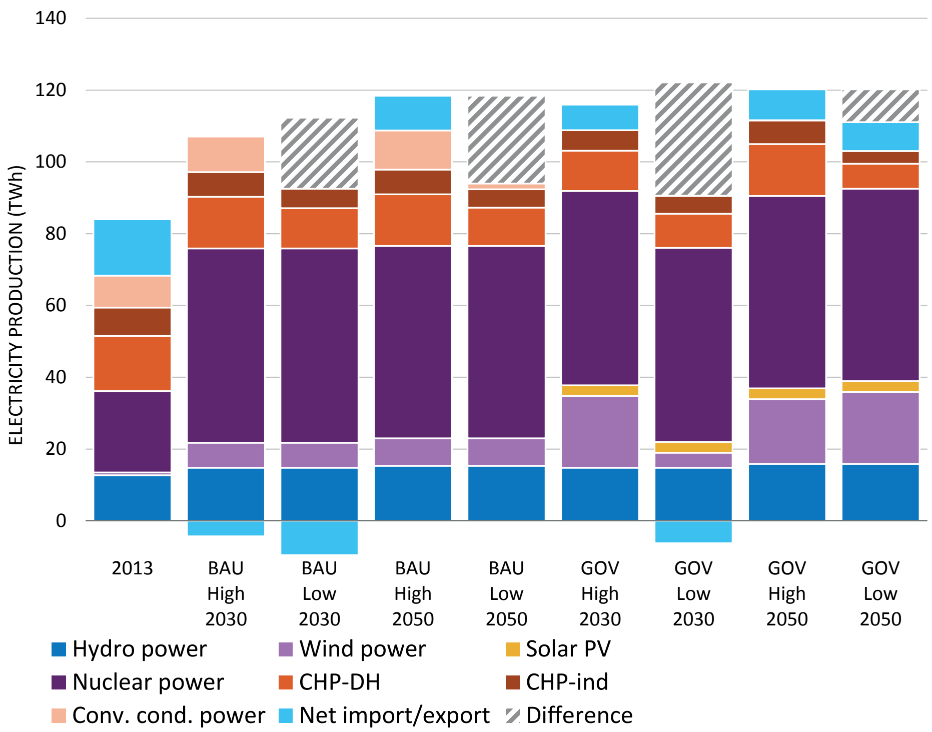


Figure 5.2: Electricity production between 2013-2050 in the BAU and GOV scenarios.

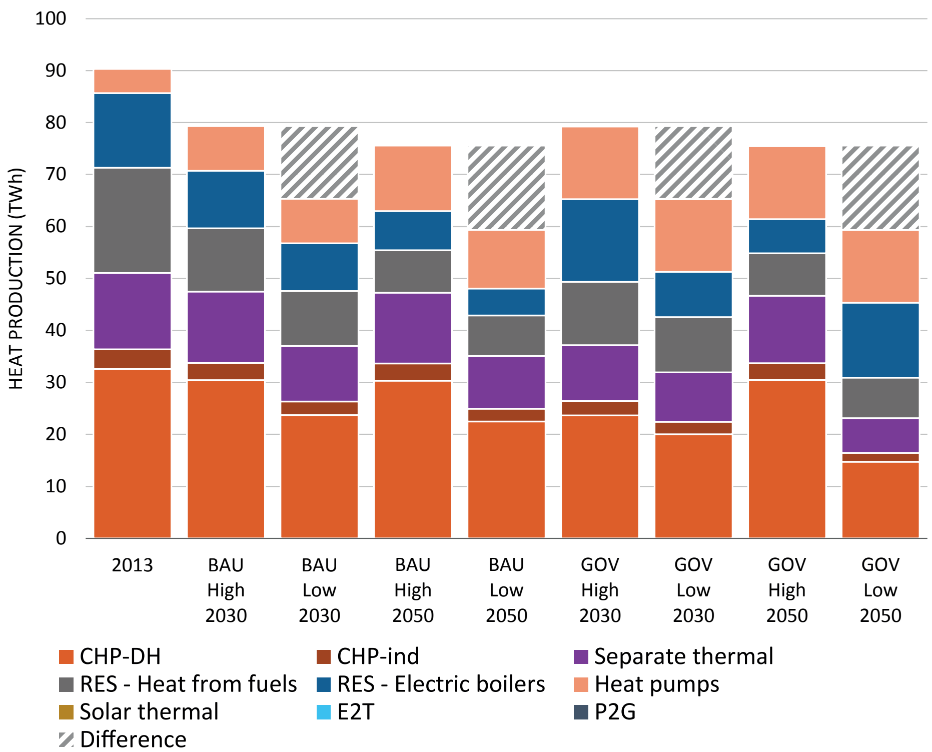


Figure 5.3: Heat production between 2013-2050 in the BAU and GOV scenarios.

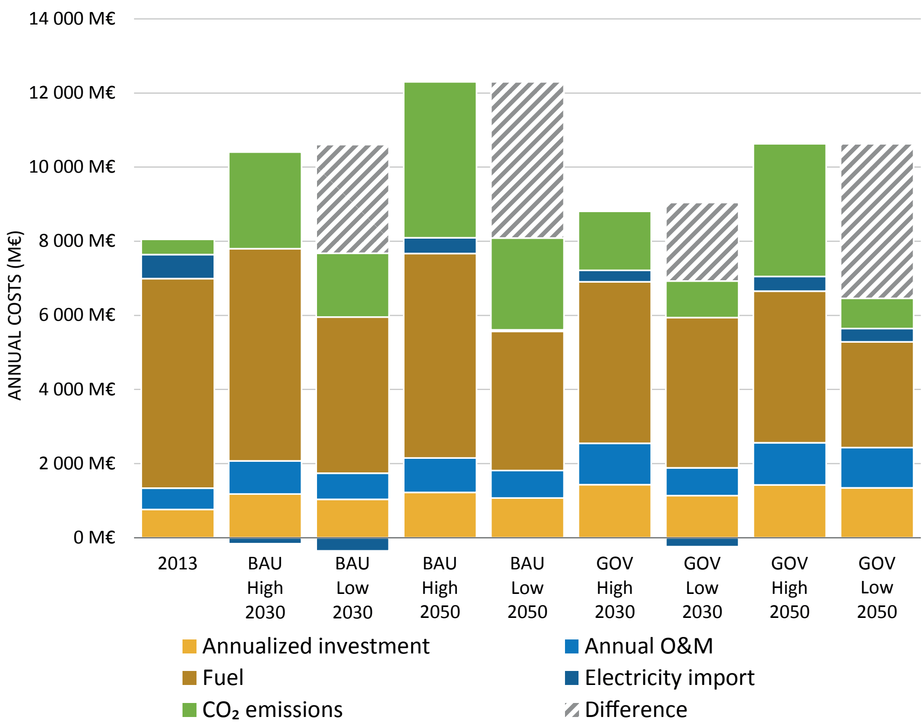


Figure 5.4: Cost development between 2013-2050 in the BAU and GOV scenarios. Note that these costs should be taken absolute since for example costs lack transmission, distribution and taxes.

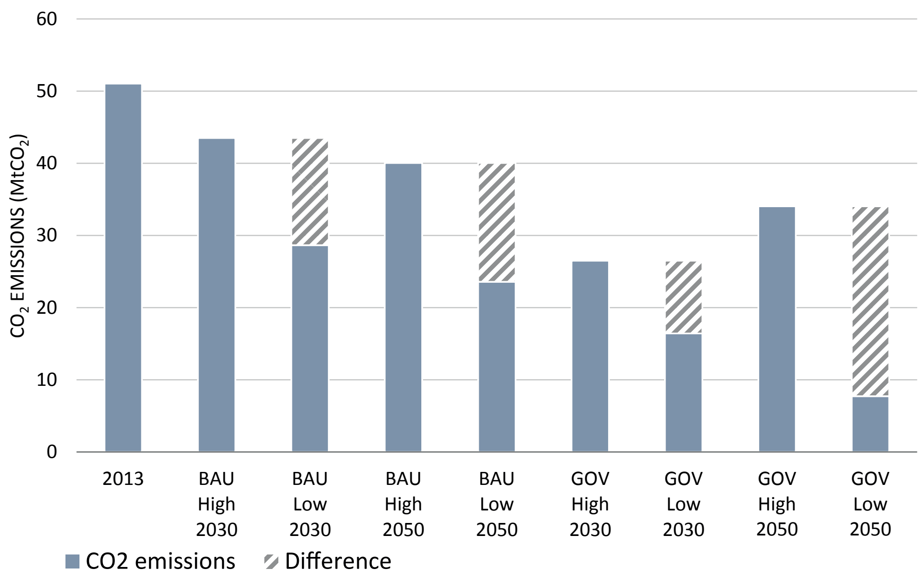


Figure 5.5: CO_2 emissions between 2013-2050 in the BAU and GOV scenarios. Note that these emissions should be used only for comparative purposes since the emission amounts are not entirely accurate.

Table 5.1: The total investment and annual costs of the BAU and GOV scenarios. These costs should only be used for comparative purposes since for example transmission is excluded from the cost calculations.

(a) Investment costs

Scenario			Investment cost (M€)	Difference to 2013	Difference to BAU
		2013	29 000		
BAU	High	2030	48 000	65 %	
	Low	2030	43 000	48 %	
	High	2050	49 000	70 %	
	Low	2050	44 000	52 %	
GOV	High	2030	53 000	84 %	11 %
	Low	2030	46 000	58 %	6 %
	High	2050	53 000	84 %	8 %
	Low	2050	51 000	75 %	15 %

(b) Annual costs

Scenario			Annual cost (M€)	Difference to 2013	Difference to BAU
		2013	8 000		
BAU	High	2030	10 000	27 %	
	Low	2030	7 000	-9 %	
	High	2050	12 000	53 %	
	Low	2050	8 000	0 %	
GOV	High	2030	9 000	9 %	-14 %
	Low	2030	7 000	-17 %	-9 %
	High	2050	11 000	32 %	-14 %
	Low	2050	6 000	-20 %	-20 %

The main difference between the BAU and GOV scenarios is the increased use of biomass, wind and solar energy and heat pumps, and the decreased use of fossil fuels. While coal was eliminated already in the scenario definition, natural gas and oil were also greatly reduced in the optimization. The main sources of fuel for the conventional conversion and industry were biomass and peat.

Since the objective function of the GOV scenario preferred renewable, domestic energy sources, biomass, wind power, solar PV and heat pumps were exploited up to their full potential. This makes the GOV scenario results highly dependent on the given potential definitions. Only in the GOV Low 2030 scenario, wind power was not utilized to its full potential, since the high amount of nuclear power already caused Finland to be a net exporter. In future studies, it might be wise to perform a sensitivity analysis on the GOV scenario results with different renewable potential limits, since the given renewable potentials seem to have a major impact on the results. In addition, especially the 3 TWh/a potential for solar PV has to be verified more closely.

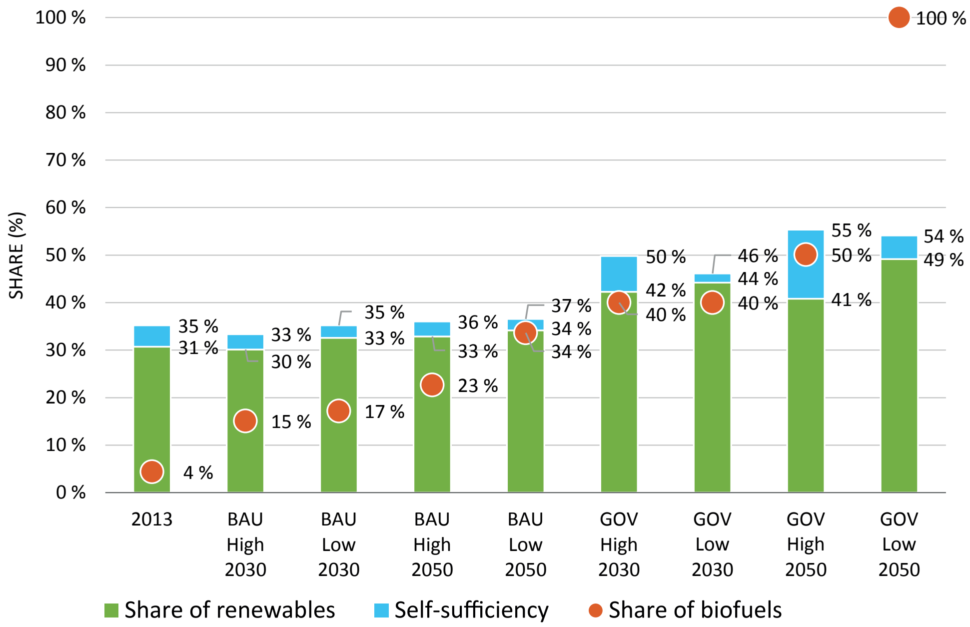


Figure 5.6: Self-sufficiency and the share of renewables between 2013-2050 in the BAU and GOV scenarios. The shares are calculated as the share of domestic or renewable sources in primary energy consumption, respectively. Hydro, biomass, waste-to-energy, wind, solar and heat pumps are considered renewable, and the domestic sources include all renewables, and peat and "others". The share of biofuels is the share of biofuels in transport fuels, not including electricity.

Even though electricity storage was available in the GOV scenarios, it was not used in the results. All available extra electricity was used in P2G for synthetic gas production. For the same reason, electricity was not exported at all, with the exception of Low 2030 scenario. On the other hand, all imported electricity was used to balance the large fluctuations of wind power production. A surprising result of the GOV scenarios was that the optimization did not prefer solar heating. Solar heating remained unused, while solar PV was utilized to its full given potential. The reason for this might be that the heat demand is at its lowest during solar thermal production times.

The heat production in GOV followed the same trends as in BAU. The share of CHP will decrease, while electricity-based heating solutions, E2T and heat pumps, will become more common. Combined with the nature of electricity production, it would seem that the government program leads to partial decentralization of the energy system: nuclear power becomes the most prominent centralized production method, together with hydro power and a decreasing amount of CHP, while decentralized heat and power sources (wind, solar, heat pumps and E2T) have an increasingly important role.

As for the costs of the GOV scenarios, the total investment costs are slightly higher in GOV than in BAU, mostly due to the increased wind and P2G capacity. However, the annual costs are actually lower in GOV, due to the lower fuel and emission costs. The CO_2 emissions in 2030 are in average -40 % lower in GOV than in BAU, and in the best scenario of this section, GOV Low 2050, the emissions reach a staggering -85 % of the 2013 level. This suggests that the GOV scenarios are cost-effective, compared to BAU.

However, the government goals of over 50 % share of renewable energy and 55 % share of domestic energy by 2030 were not met, as seen in Fig. 5.6. Trying to find a solution for the GOV scenario, in which the share of renewable sources exceeded 50 % without breaking the projected export capacities and/or potential limits, required numerous optimization iterations with different goals and target functions, with no success. The multi-objective target function shown in 4.4.2 provided the closest approximate. However, the government goal for renewable transport fuels, 40 %, was met easily.

The reason for this difficulty might be that the goals of the government programme were stated vaguely. It was not clear whether the shares of domestic and renewable sources were meant to be measured from the total primary energy use, as assumed in this study, or from the final energy use. As non-renewable sources tend to have high conversion losses, the share of renewable sources can easily be a lot higher if measured from the final energy use.

In all BAU and GOV scenarios, biomass will remain the backbone of the Finnish renewable energy, despite the full utilization of wind and solar potentials. However, the renewability of biomass might come under debate in the future. Biomass is usually considered renewable, as while burning biomass releases greenhouse gases, it is assumed that the growing forest re-absorbs the emitted carbon dioxide. Any change in biomass sustainability criteria will radically affect the share of renewables in the Finnish energy system. Additionally, the role of peat will increase in all GOV scenarios. In Finland, peat is classified as "slowly renewable biomass fuel" and peat-based electricity is subsidized by the Finnish government, which is criticised by IEA. [6]. However, the government aim of reducing fossil fuel consumption seems to lead to an increased peat usage.

It can be argued that the GOV scenarios did not fully utilize the different P2X technologies, as electricity storage and E2T conversion were not substantially used. However, since all available electricity overproduction was used in P2G and the renewable potentials were fully exploited, it may have been that there was simply not enough renewable electricity production to utilize E2T or electricity storage. In a sense, P2G acted as the electricity storage since it could shift the electricity overproduction temporally, by converting it to time-independent fuel. More P2X operation might be achieved with higher renewable potentials, especially wind potential, since the results seem to be sensitive to the given potential.

5.2 Limits of VRE addition

In this study, we tested the effect of P2X technologies on VRE integration. Different P2X technologies, including E2T, P2G and electricity storage, were gradually enabled in the system, and the VRE integration was maximised as stated in 4.4.3. Only the 2013 consumption scenario was used in this study. The results are shown in Figs. 5.7-5.10 which present the share of VRE in primary energy and in electricity production, and the structure of electricity and heat generation.

It can be clearly seen from Fig. 5.7 that the inclusion of P2X increases VRE integration, particularly wind integration, as seen in Fig. 5.8, and the amount of the maximum wind power varies depending on the P2X technologies included. However, solar PV was not added in the same scale as wind. The reason for this may be that the wind power coincides with the demand better than the summer-centred solar power. Even though the solar overproduction could have been stored and converted into heat in the autumn, or used in P2G production, wind power was preferred this kind of operation. The same kind of result was also discovered by Zakeri et al. [3], as they noticed that solar integration does not increase renewable electricity, as solar integration constrains wind integration, although the costs increase significantly.

The highest VRE integration level, 51 % of primary energy consumption and 83 % of electricity production, was in the cases P2G and P2G+Sto. The high integration level was caused by replacing all industrial fuel and the fuel needed in separate heat production with P2G gas. This is not the most economical solution, because the heat from synthetic gas is produced through the combined conversion efficiency of P2G and heat boilers. However, the high amount of VRE primary energy required for this substitution causes the VRE share in the primary energy consumption to be

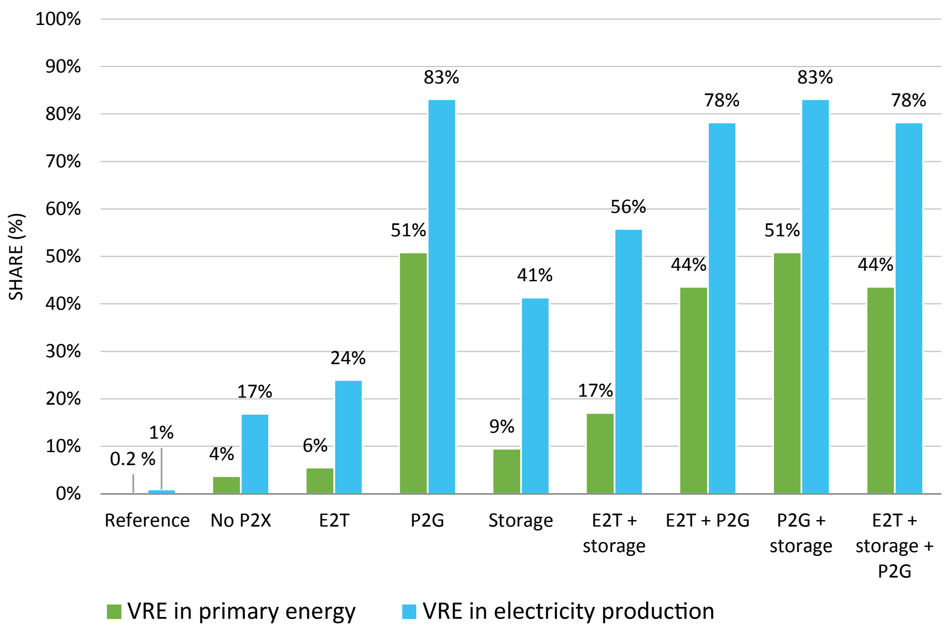


Figure 5.7: Maximum VRE integration with different P2X combinations.

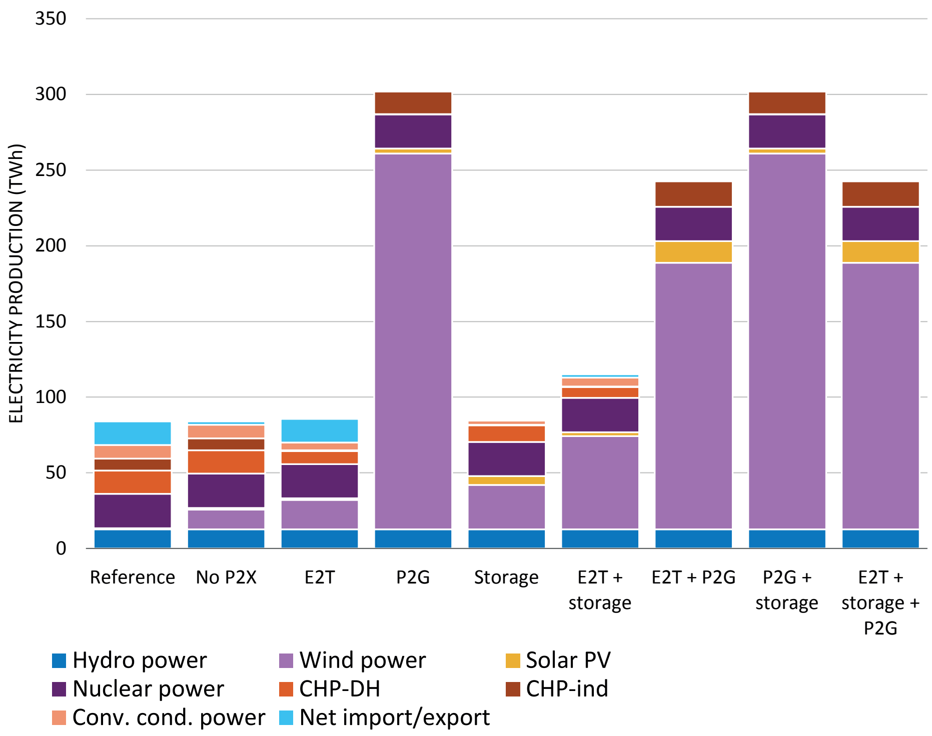


Figure 5.8: Electricity production with different P2X combinations.

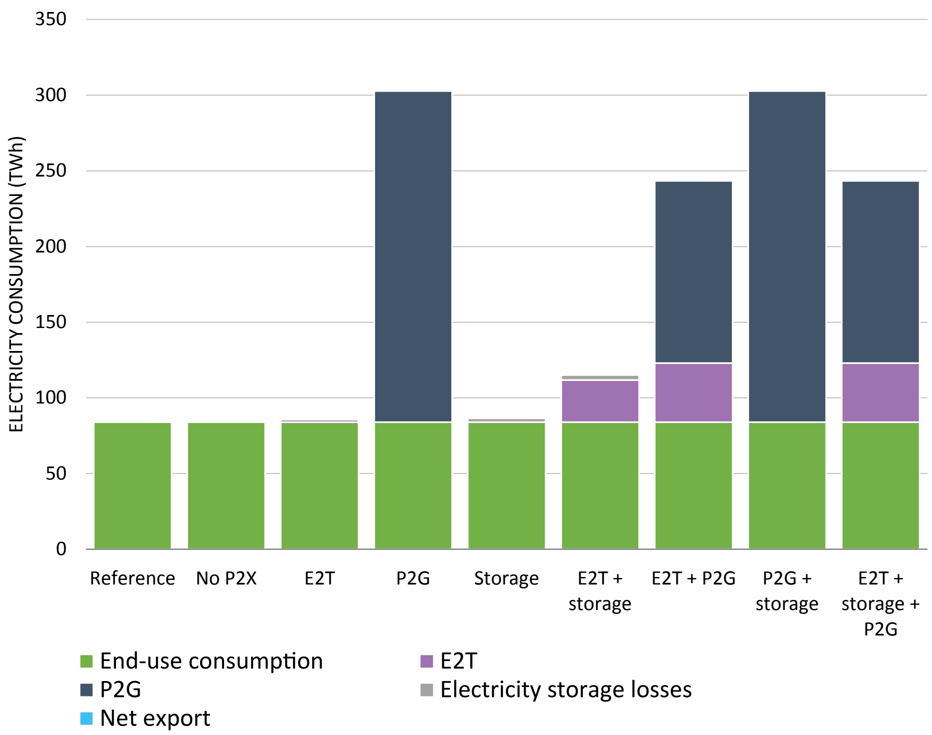


Figure 5.9: Electricity consumption with different P2X combinations.

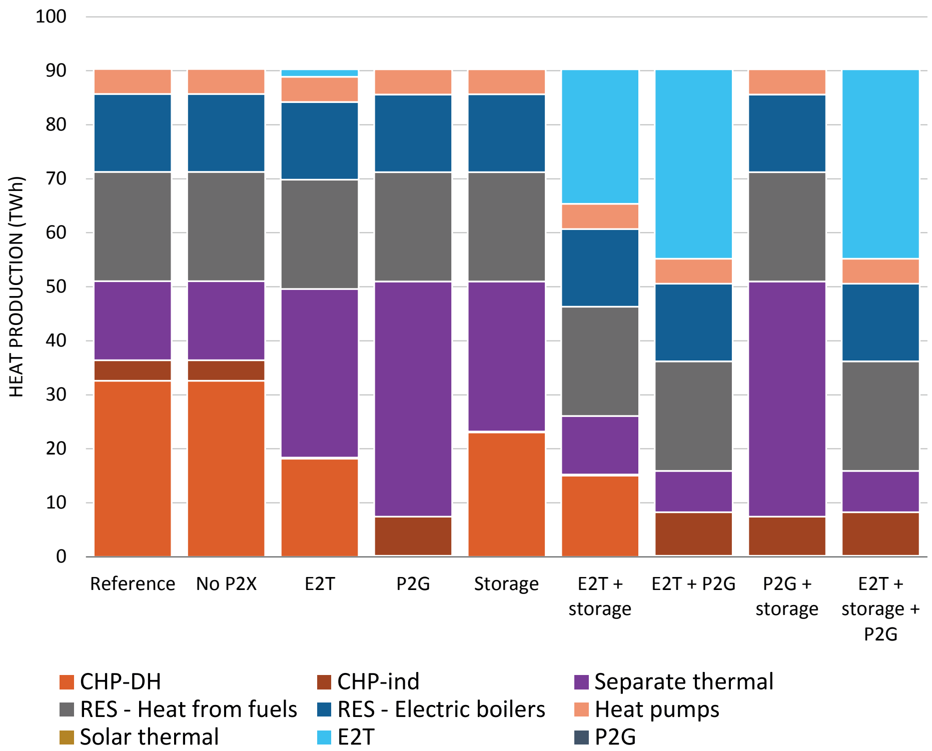


Figure 5.10: Heat production with different P2X combinations. Residential heat from fuels, electric boilers and heat pumps remained unchanged in the scenarios.

disproportionally high, favoured by the optimization target function.

The second highest VRE integration level, 44 % of primary energy consumption and 78 % of electricity production, was for the combination of E2T and P2G. The energy flow diagram of this case can be found in Fig. C.10. The combination of E2T and P2G allowed generating most of the heat demand with E2T, and P2G-based gas was mostly used to cover the industrial fuel demand, although some heat was generated also with P2G gas.

Since the model allows E2T operation only to fill the current heat demand, not to charge heat storage, including only E2T without electricity storage did not increase VRE integration very much, only 2 %-units in primary energy compared to the no P2X case. Including only storage increased VRE integration by 5 %, but the combination of E2T and storage increased VRE integration by 13 %, more than the individual inclusions of E2T and storage combined. On the other hand, all cases including P2G had very high VRE integration levels, again due to the poor conversion efficiency of producing heat with P2G gas.

One interesting notion from the results is that whenever P2G was included, the addition of electricity storage did not affect VRE integration. This result is in line with the conclusion from the GOV scenarios, where P2G practically voided the need for electricity storage. It was more beneficial to convert all available VRE overproduction directly into gas, than storing the electricity for later use. However,

Table 5.2: The total investment and annual costs with different P2X combinations. Note that the reference costs differ slightly from Table 5.4 because in the VRE study, the primary energy input was slightly modified (fossil fuels partly replaced by biomass and coal, see 4.4.3).

Case	Investment cost (M€)	Difference	Annual cost (M€)	Difference
Reference	29 000		8 000	
No P2X	36 000	25 %	8 000	1 %
E2T	35 000	22 %	8 000	4 %
P2G	148 000	413 %	15 000	100 %
Sto	51 000	78 %	8 000	11 %
E2T+Sto	68 000	135 %	10 000	25 %
E2T+P2G	127 000	337 %	13 000	68 %
P2G+Sto	148 000	413 %	15 000	100 %
E2T+P2G+Sto	127 000	337 %	13 000	68 %

this phenomenon might be the result of the model's dual time scale: electricity and heat are modelled on an hourly level, whereas fuels are considered only on a yearly level. This also means that fuel demand is seen as time-independent.

Similarly to electricity storage, heat storage was also not needed in all the cases. Heat storage was required in the cases Reference and No P2X (0.047 TWh), E2T (0.002 TWh) and Storage (0.006 TWh), and in all the other scenarios, heat storage was absent. This might be due to more flexible heat generation solutions, either with E2T or separate heat production. Furthermore, the cases which utilize electricity storage are Storage (1.779 TWh) and E2T+storage (2.093 TWh). In terms of costs, these electricity storage capacities equals 6 400 M€ of investment costs and 200 M€/year of O&M costs for the 1.8 TWh storage, and 10 300 M€ and 300 M€/year for the 2.1 TWh storage, in the 2013 prices.

Figures 5.8 and 5.9 show the electricity production and consumption structure of the different cases. It can be clearly seen that the high amount of wind power in P2G cases is mostly used in P2G operation, and in general P2G uses higher amounts of electricity than E2T. The heat production structure, shown in Fig. 5.10, also varies with P2X technology inclusion. The cases with the higher amounts of wind power show a shift from district heating to separate heat production and industrial CHP. This might be due to separate heat production being more flexible than CHP-DH, allowing better load-following. Additionally, industrial CHP might be preferred because it provides flat base heat production, compared to the varying CHP-DH.

The costs of the VRE cases are presented in Table 5.2. It was already mentioned in section 4.4.3 that as the optimization is purely technical, the resulting systems are not economically feasible. It can be seen that especially P2G causes very high increases to investment and annual costs. However, it was discovered that the investment and annual costs follow linearly the amount of wind power, with R^2 values of 0.986 and 0.998 respectively, so the cost of the P2G technologies themselves does not affect the costs significantly.

Chapter 6

Summary

In this work, we modelled the Finnish energy system in 2013 and in the future on a macro level. A novel, two-phase conversion methodology was created, with a special focus on the advanced conversion methods between final energy forms. The energy system was modelled with a module-based bottom-up-type methodology starting from primary energy sources and ending in final energy demands. All aspects of the energy system were taken into account, including electricity, heat and fuel. Demands were discussed by sector, including residential and public sectors, process industry, other industry and transport. The industrial sector was separated into process and non-process industry to capture the importance and the specific demands of the Finnish forest industry. The accuracy of the model was one hour for electricity and heat, and one year for fuels.

Based on this methodology, we developed an Excel-based computer model. Excel was chosen as the platform due to its user-friendliness and immediate visible calculations. The model allowed exploring various scenarios, for example renewable energy additions and advanced conversion technology inclusion. Cost analysis was also included in the model. However, being a macro-level model, the operational side of the model was rather simplified, and it should not be used for accurate system operation simulation.

The model was used to carry out analysis of future scenarios, for the years 2030 and 2050. In order to explore different possible future pathways, we used two different consumption scenarios: "high" and "low". In the "high" scenario, consumption will generally increase, whereas in the "low" scenario, consumption will mostly decrease due to energy-saving policies. As for the production, we considered two main scenarios: business-as-usual (BAU) and the current government programme (GOV) with goals such as abandoning coal, cutting the oil usage in half and increasing the share of domestic fuels to 55 %. In addition to the BAU and GOV scenarios, we studied the addition of wind and solar power to the existing system, with the goal of exploring the maximum possible integration using different advanced conversion technologies.

The results indicated that Finland will be net electricity exporter in 2030 in the business-as-usual scenario, mainly due to the increased nuclear capacity, but in 2050 again a net importer due to an increased electricity consumption. Combined heat and power (CHP), which is nowadays an integral part of the Finnish energy system, will become less important in the future, as heat demand decreases and heat production becomes more electrified. The cost of the energy system will increase in the "high" consumption scenario and remain the same in the "low" scenario, but the structure of the costs will change. An increased carbon dioxide emission price will lead to significantly higher costs, even though the carbon emissions will actually decrease already in the business-as-usual scenario.

The government scenarios were similar to the business-as-usual scenarios, but the self-sufficiency and renewable energy goals resulted in higher amounts of biomass, wind and solar power, as well as peat. Even though all renewable resources were fully exploited, the model was unable to find a solution where the government goals of over 50 % share of renewable energy and 55 % share of domestic energy by 2030 were not met. There are several possible reasons for this. Firstly, it became clear that the model is sensitive to the given maximum potentials of renewable energy sources. Secondly, the high amount of nuclear power, which is neither renewable nor domestic, appeared to be difficult to compensate. Thirdly, it was not clear whether the shares should have been calculated from primary or final energy consumption. However, most of the government goals were met, including the removal of coal, cutting oil import and increasing the share of biofuels in transport. Lower utilization of fossil fuels also resulted in lower costs and emissions than business-as-usual.

In both BAU and GOV scenarios, biomass remained the backbone of the Finnish renewable energy, whereas nuclear power is the backbone of electricity production. A surprising result of the GOV scenario was that solar heat or electricity storage were not utilized almost at all, even though they were both available and could have increased the renewable energy integration. Instead, all available electricity surplus was used in power-to-gas (P2G) or electric heating (E2T).

The results of the wind and solar addition study showed that especially power-to-gas has the potential of greatly increasing wind integration, as wind energy can be used to substitute fossil fuel. Electricity-to-thermal (E2T) and electricity storage also increased renewable integration, since E2T could be used to replace the fuel-based CHP heat production and storage allowed temporally shifting the variable renewable power to more beneficial occasions. However, without storage E2T was not able to increase the VRE integration very much, since wind and solar production tended not to coincide with heat demand and the model did not allow charging the heat storage "beforehand" with E2T. Similarly to the GOV scenario, it was found out that P2G practically voided the need for the electricity storage, since the electricity surplus was rather converted to gas than stored.

For future studies, we will consider several improvements to the energy system model. Firstly, we will re-define the renewable energy potential to which the results seem highly sensitive. Especially the 3 TWh/a potential of solar PV might be too low. Secondly, we will refine the storage operation. In this work, all the losses of the heat and electricity storage were taken into account as a round-trip efficiency, but in reality, the storage losses have a temporal aspect and storages have constant losses. Thirdly, the modelling accuracy of fuel may need to be reconsidered. The current accuracy of one year is too low for modelling the fuel, especially gas, storages during the year, and fuel could be modelled for example on a seasonal level in future. Fourthly, on the primary energy level, biogas could be separated to its own primary energy source, and oil and biogas refineries could be added to the module structure. After all, biogas has a different functionality and different sources as wood-based biomass, such as black liquor and forest chips. Finally, what could be reconsidered is the model's simplified treatment of hourly production data. The hourly production profiles of for example CHP are rigid in the model, but in reality, most of the conventional power and heat production can be adjusted to demand. However, this kind of operation optimization requires a more detailed optimization methodology, and a simplified macro-level model could still be detailed enough to study the broader future developments.

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Appendix A

User instructions

The energy balance model is implemented with Microsoft Excel, and it consists of fourteen worksheets. Their descriptions are listed in Table A.1.

Table A.1: The descriptions of the model's worksheets. The first four sheets, marked green in the model, are the most essential for using the model. The second group, marked white in the model, are the more detailed information about the operation, including the hourly data and graphs. The last group, marked violet in the model, contains all the input data, and since they are not often used, they are hidden.

Worksheet	Description
Energy balance	Front page of the model, showing the energy flows in an annual scale. Scenario changes and P2X inclusion are made here. This sheet follows the model structure (Fig. 3.2), proceeding from top to bottom. Uppermost are the main operation success labels, indicating whether the scenario fulfils all the requirements.
Conditions	Preference orders of P2X technologies and conversion efficiencies.
Production	Summary of electricity and heat production and their boundary conditions
Costs	Cost analysis.
Electricity	Hourly electricity data.
Heat	Hourly heat data.
Graphs	Graphical outputs.
Scenarios	Management of saved production scenarios.
Consumption	Predefined consumption scenarios for 2030 and 2050.
Graph data	Data for the graphs.
Heat demand model	Modelling the heat demand from temperature data.
Electricity data	Reference hourly electricity data.
Other data	Other input data used in the model.
STAT	The Finnish energy balance sheet.

A.1 Loading input data

The input data can be loaded to the hidden worksheets. Throughout the model, the cells where any input data should be located are marked with light violet. The required input data are

- Energy balance sheet
- Hourly electricity data
- Outside temperature data
- Electricity prices
- Storage capacities and error margins

Additionally, the following data has to be uploaded at least once:

- P2X conversion efficiencies
- Solar production data
- Cost assumptions
- Consumption scenarios

A.2 Building scenarios

The most important worksheet in building scenarios is "Energy balance", with "Conditions" as the second. The cells that may be changed are marked with light violet. Changeable cells include (the corresponding worksheet in brackets)

- Changes to primary energy input (Energy balance)
- Fuel allocation in conventional conversion (Energy balance)
- Consumption scenario (Energy balance)
- Storage constraints and error margins (Energy balance)
- P2X preference orders (Conditions)
- P2X conversion efficiencies (Conditions)
- Cost assumptions (Costs)
- Year for cost assumptions (Costs)
- Storage start value (both Electricity and Heat)
- Cut-off price for storing electricity (if applicable) (Electricity)

In addition, the model employs several ON/OFF switches. If the switch can be used, the red or green color is darker and the font is bold and italic. The switches can be found mostly in P2X module inclusion.

When starting to build a scenario, one should first choose the consumption scenario to use. In "Energy balance", from row 90 onwards, the consumption scenario can be selected and erased. If the heat demand changes, new heat demand has to be

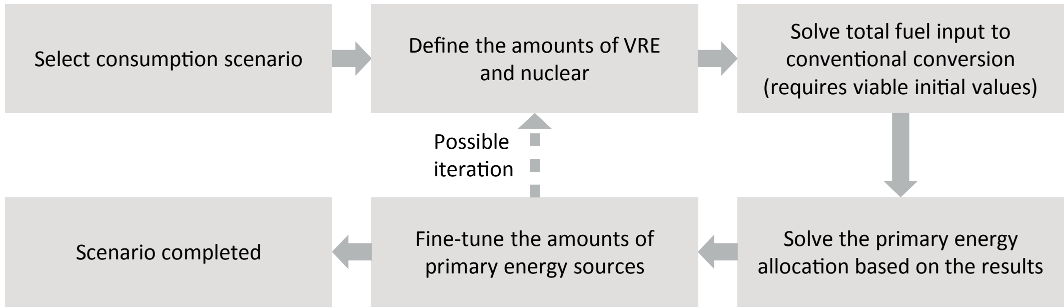

Figure A.1: Phases of building a scenario based on consumption, according to one method.

calculated separately (requires the Solver add-in). The predefined consumption scenarios are already grouped, but if the user wishes to use an ungrouped scenario starting from the primary energy sources, one should press the "Use STAT data" button to have the correct formulas. After uploading the consumption, the correct year for cost calculations and transmission capacities should be selected in "Costs" and "Production" sheets, as they do not change automatically.

After setting the consumption and the correct year for costs, one should select the advanced conversion modules to be used by switching the respective labels on/off, and check the P2X preferences in "Conditions". After this, the user can start the more or less manual task of changing the amount of primary energy input and their allocation to conventional conversion methods. One method, also shown in Fig. A.1, is first to define the amount of nuclear and renewable energy (hydro, wind, solar), and then the total amount of fuel to each method, without any consideration of primary energy sources, and finally use the Solver to determine the actual amounts of different primary energy sources. There are predefined macros to help in this kind of conventional conversion allocation, found in the "Allocation help" box. The nuclear and VRE should be determined before using these macros.

However, the flexible structure of the Excel allows building scenarios with a variety of methods. In this thesis, optimization was performed to maximize predefined objective functions, using several different variables. The exact scenario-building method depends on the problem. As a visual aid, there are automatic flags to inform the user about the success of the scenario in the uppermost part of the "Energy balance" worksheet.

When a scenario is changed, most of the calculations are immediate. However, after changing the preference order in "Conditions", the update button should be pressed. In "Graphs", the energy flow diagram has to be updated by pressing the update button as well.

Production scenarios can be saved and uploaded from the "Scenarios" sheet. When saving scenarios, one can either overwrite an existing one or create a new save. When uploading scenarios, please note that uploading takes time since not only data is uploaded, but the macros concerning i.a. consumption, flow chart and P2X conversion are also run.

Appendix B

Supporting numerical data

Table B.1: Parameters of the reference scenario. The set parameters are the inclusion of P2X technologies, storage capacities and assumed P2X conversion efficiencies.

Parameter			Value
P2X conversion	E2T		FALSE
	Biofuel conversion		FALSE
	P2L		FALSE
	P2G		FALSE
	Elec storage		FALSE
Storage capacities	Heat	$S_{\text{heat,max}}$	0.05 TWh
	Electricity	$S_{\text{elec,max}}$	0.00 TWh
Conversion efficiencies	RES-E2T	$\eta_{\text{RES}-\text{E2T}}$	95 %
	E2T	η_{E2T}	90 %
	P2G - gas	$\eta_{\text{P2G,gas}}$	40 %
	P2G - heat	$\eta_{\text{P2G,heat}}$	20 %
	P2L	η_{P2L}	80 %
	Biofuel conversion	η_{bio}	80 %
	Heat pump	$COP_{\text{heat pump}}$	4.5
	Heat storage	$\eta_{\text{sto,heat}}$	90 %
	Electricity storage	$\eta_{\text{sto,elec}}$	90 %

Table B.2: Consumption scenarios used in the thesis. The arrows indicate the overall trend between 2013 and 2050.

	Unit	Sector	Reference 2013	High 2030	High 2050		Low 2030	Low 2050	
Electricity	TWh	Total	68.9	91.1	110.5	↑	73.4	88.5	↗
		Process industry	33.7	38.5	45.1	↗	31.3	29.6	↘
		Other industry	6.5	12.2	15.4	↑	11.4	18.2	↑
		Transport	0.7	2.9	7.5	↑	1.8	5.4	↑
		Residential	9.8	15.1	17.7	↑	11.1	14.9	↑
		Public sector	15.6	19.3	21.2	↗	15.3	17.5	↗
		Losses	2.6	3.1	3.6	↗	2.5	2.9	↗
Heat	TWh	Total	90.3	79.3	75.5	↘	65.3	59.3	↘
		Process industry	13.1	13.7	14.2	↗	12.3	11.3	↘
		Other industry	4.2	4.1	4.0	↔	3.3	3.3	↘
		Residential	50.3	41.2	37.5	↘	33.5	29.4	↓
		Public sector	18.9	16.9	16.5	↘	13.6	13.0	↘
		Losses	3.7	3.4	3.3	↔	2.5	2.3	↓
		District heat	51.0	49.2	48.5	↔	38.5	35.9	↘
		Heat from fuels	20.2	12.2	8.1	↓	10.6	7.8	↓
		Electric boiler heat	14.4	9.2	6.3	↓	7.6	4.4	↓
		Heat pumps	4.6	8.6	12.6	↑	8.6	11.3	↑
Fuel	PJ	Process industry	117	113	111	↔	92	91	↘
		Other industry	27	26	26	↔	21	21	↘
		Must-run biomass	134	149	161	↗	144	126	↔
		Transport fuels	211	196	193	↘	165	121	↓
Total	PJ		1 063	1 098	1 160	↗	921	891	↘
				+3 %	+9 %		-13 %	-16 %	

Appendix C

Energy flow diagrams

This section presents the energy flow diagrams of all the BAU and GOV scenarios, and one scenario from the VRE addition study as an example. The unit of the diagrams is TJ. The energy flows are presented as a Sankey diagram, in which the width of the arrows is proportional to the flow quantity. The quantity of each energy flow is shown in the flow label, and the conversion nodes show the quantities of input and output.

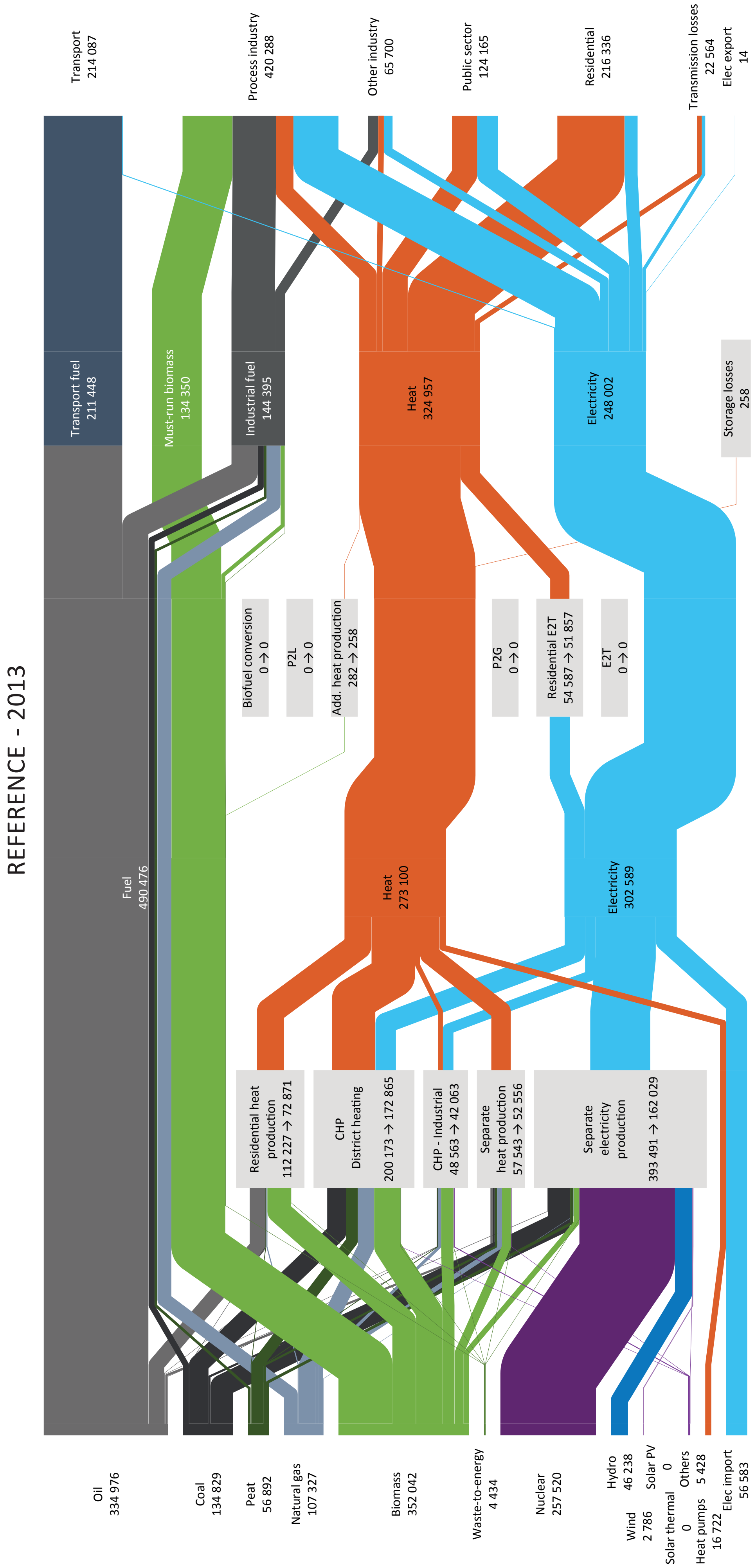

Figure C.1: Reference scenario, 2013.

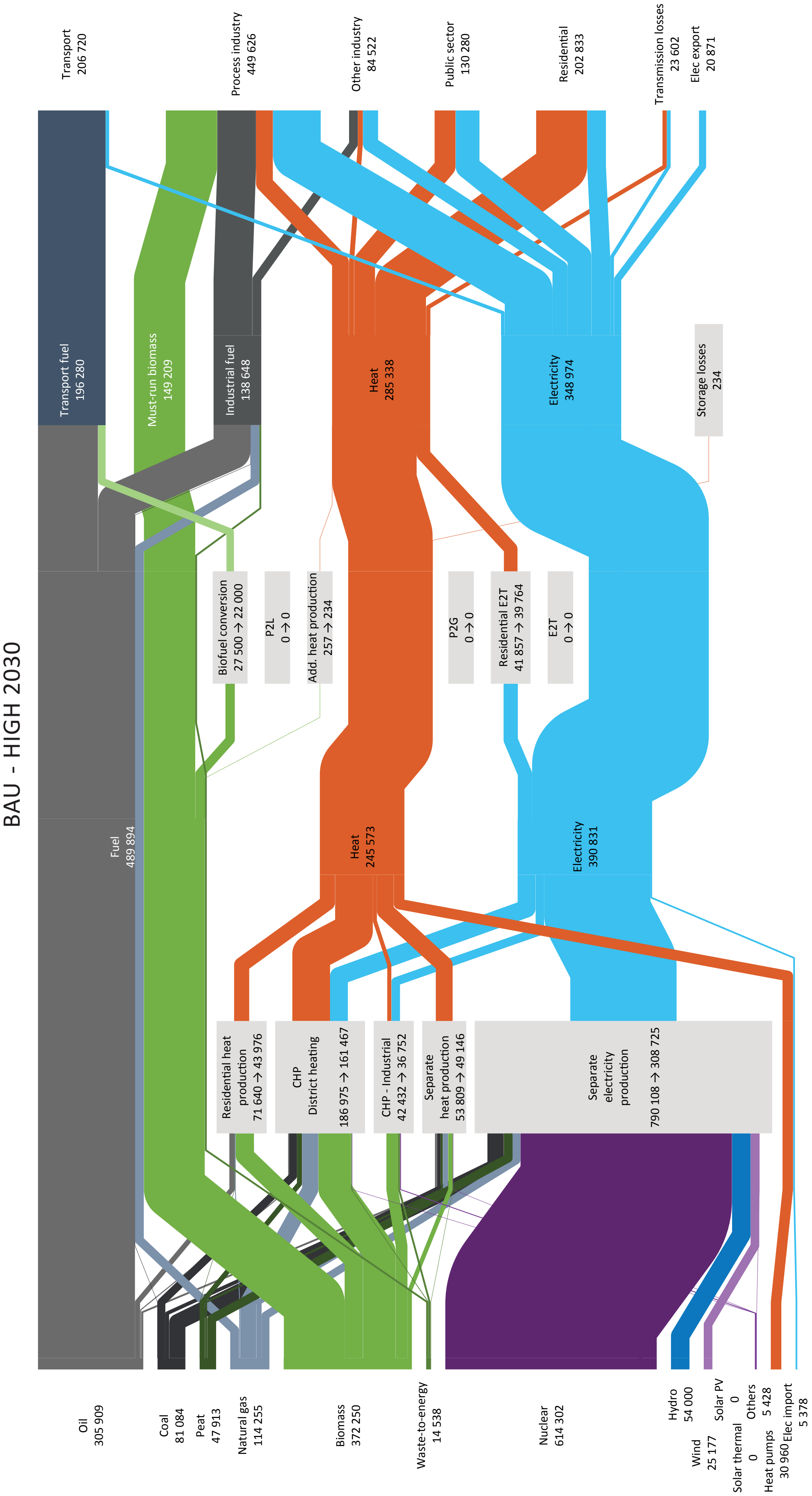

Figure C.2: Business-as-usual with high consumption scenario, 2030.

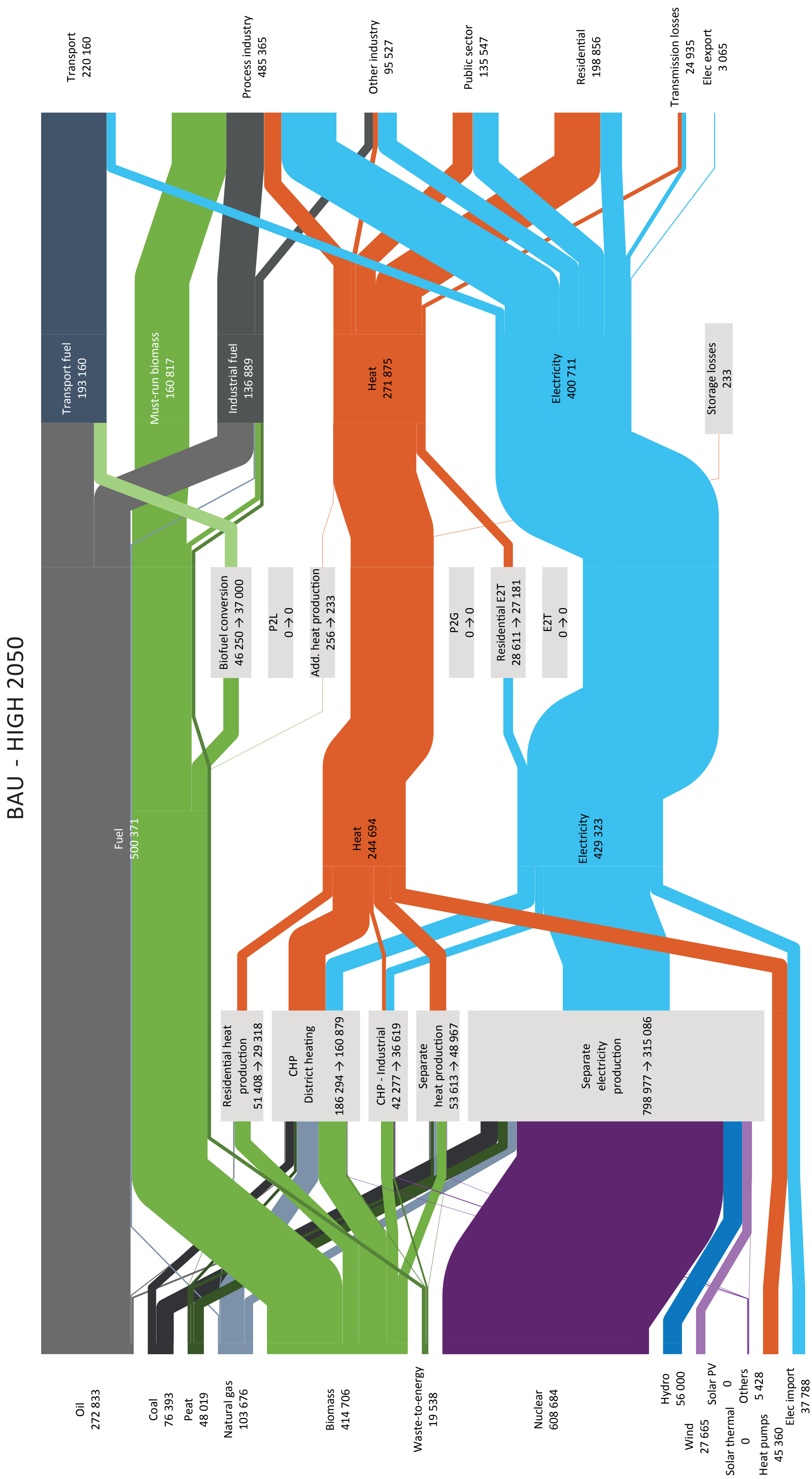

Figure C.3: Business-as-usual with high consumption scenario, 2050.

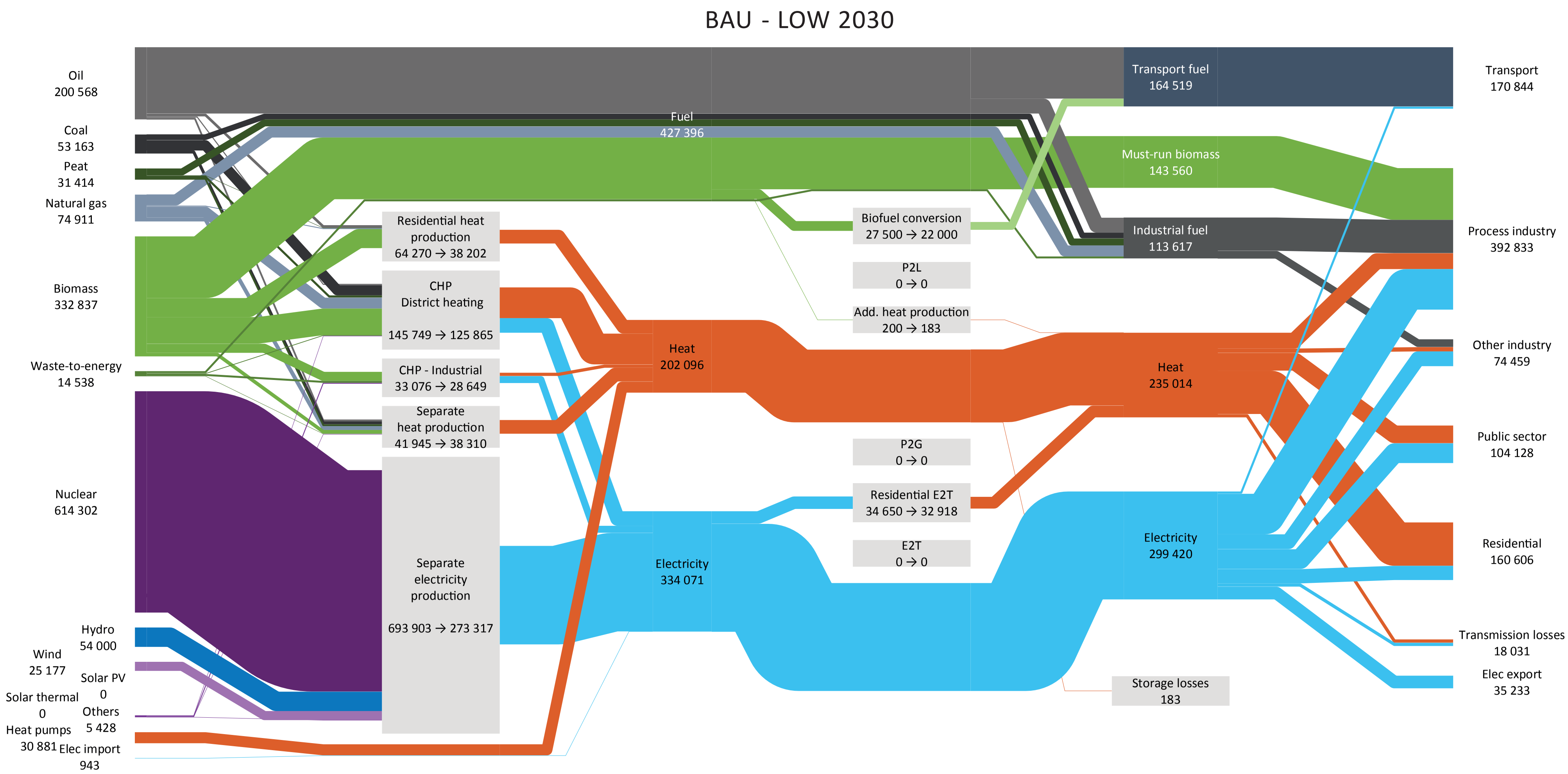

Figure C.4: Business-as-usual with low consumption scenario, 2030.

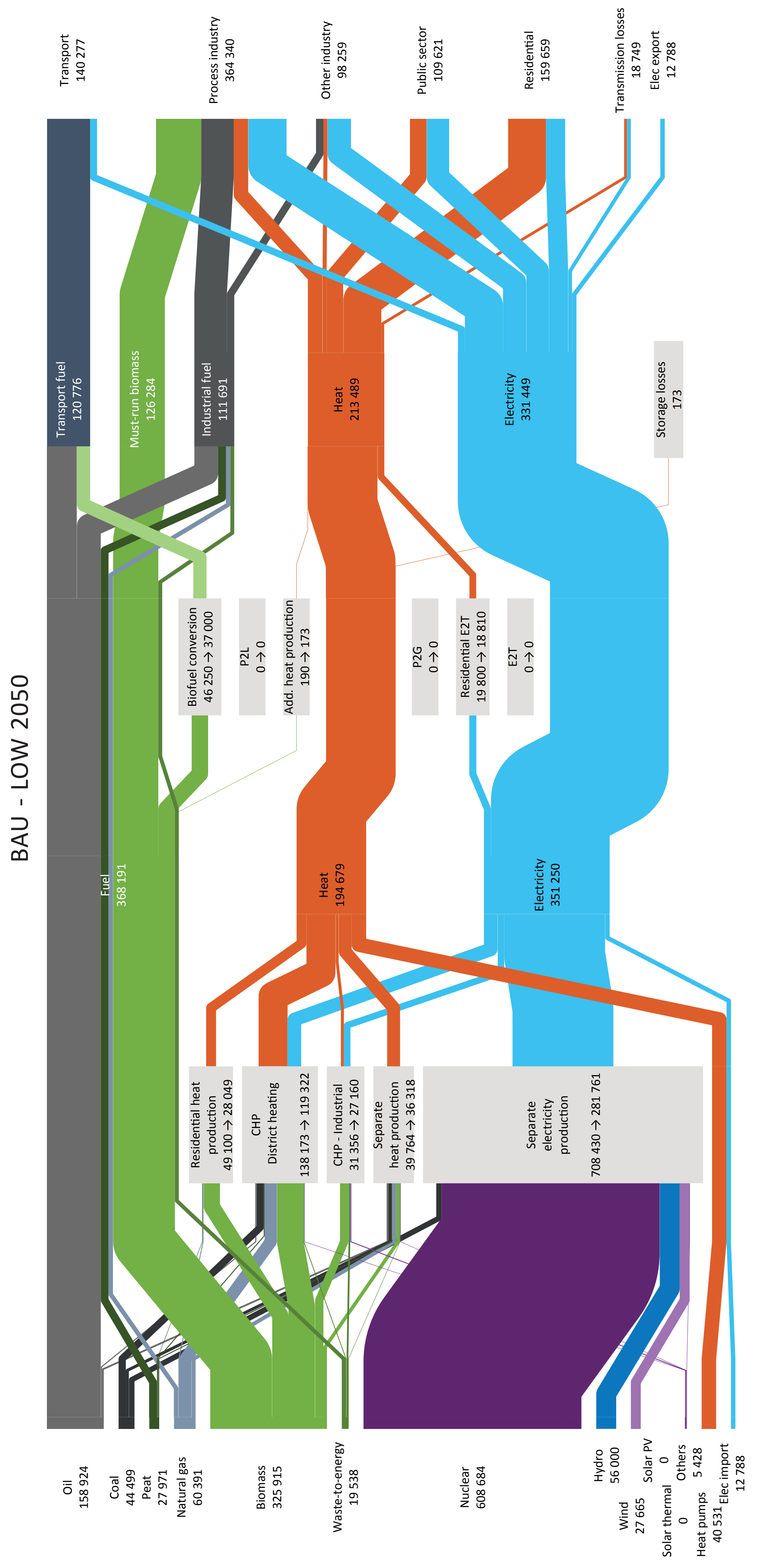

Figure C.5: Business-as-usual with low consumption scenario, 2050.

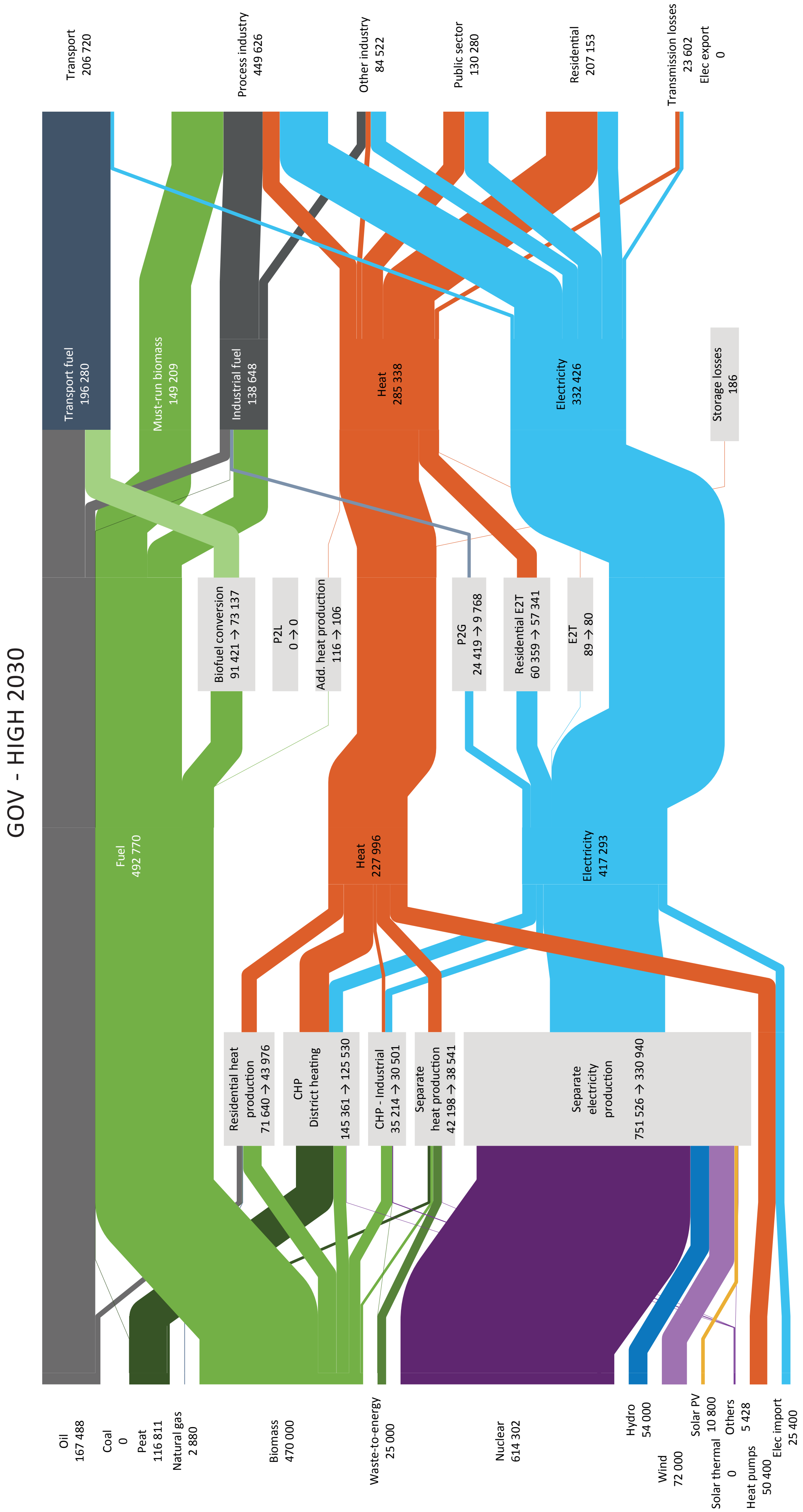

Figure C.6: Government scenario with high consumption scenario, 2030.

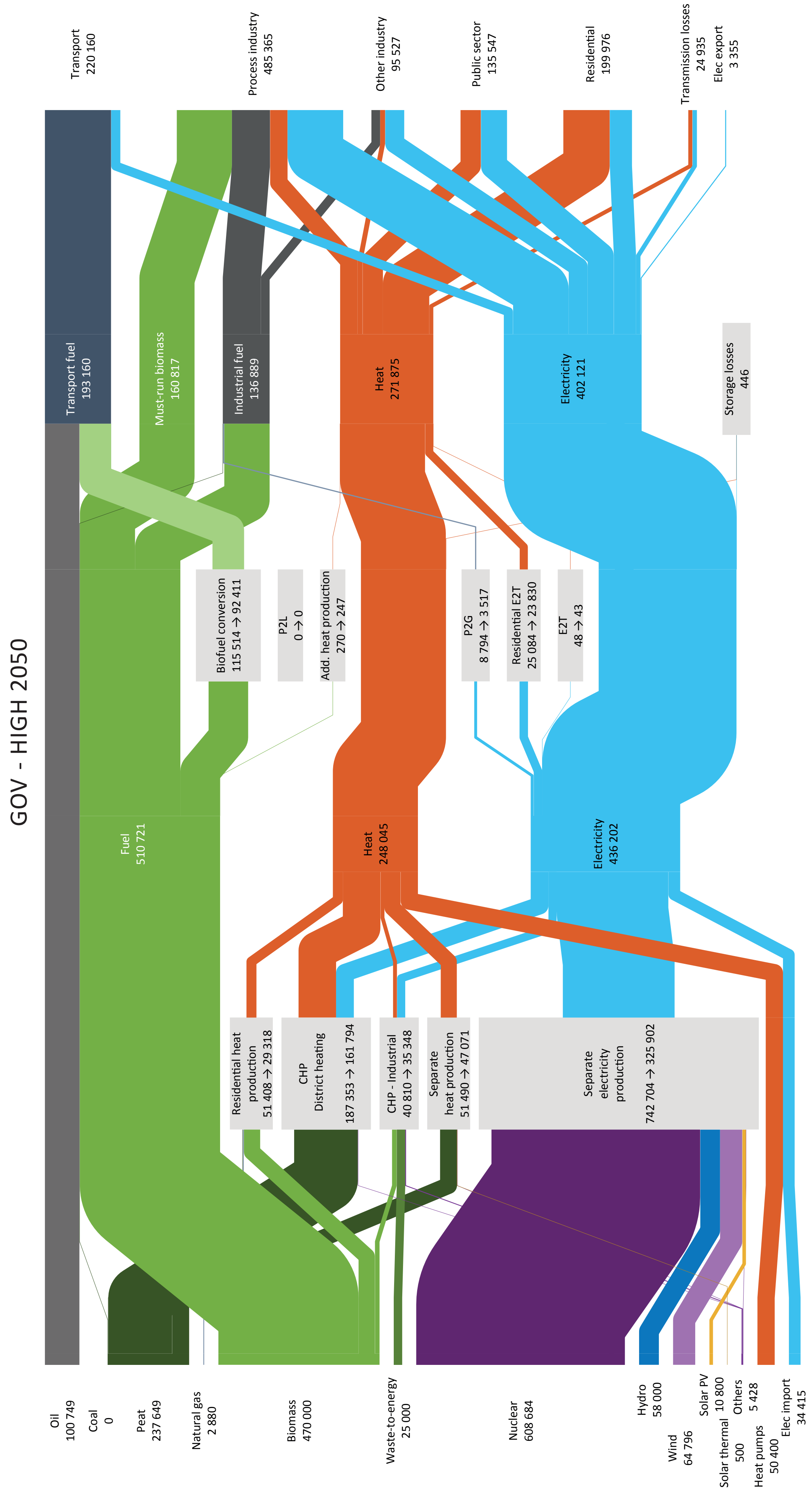

Figure C.7: Government scenario with high consumption scenario, 2050.

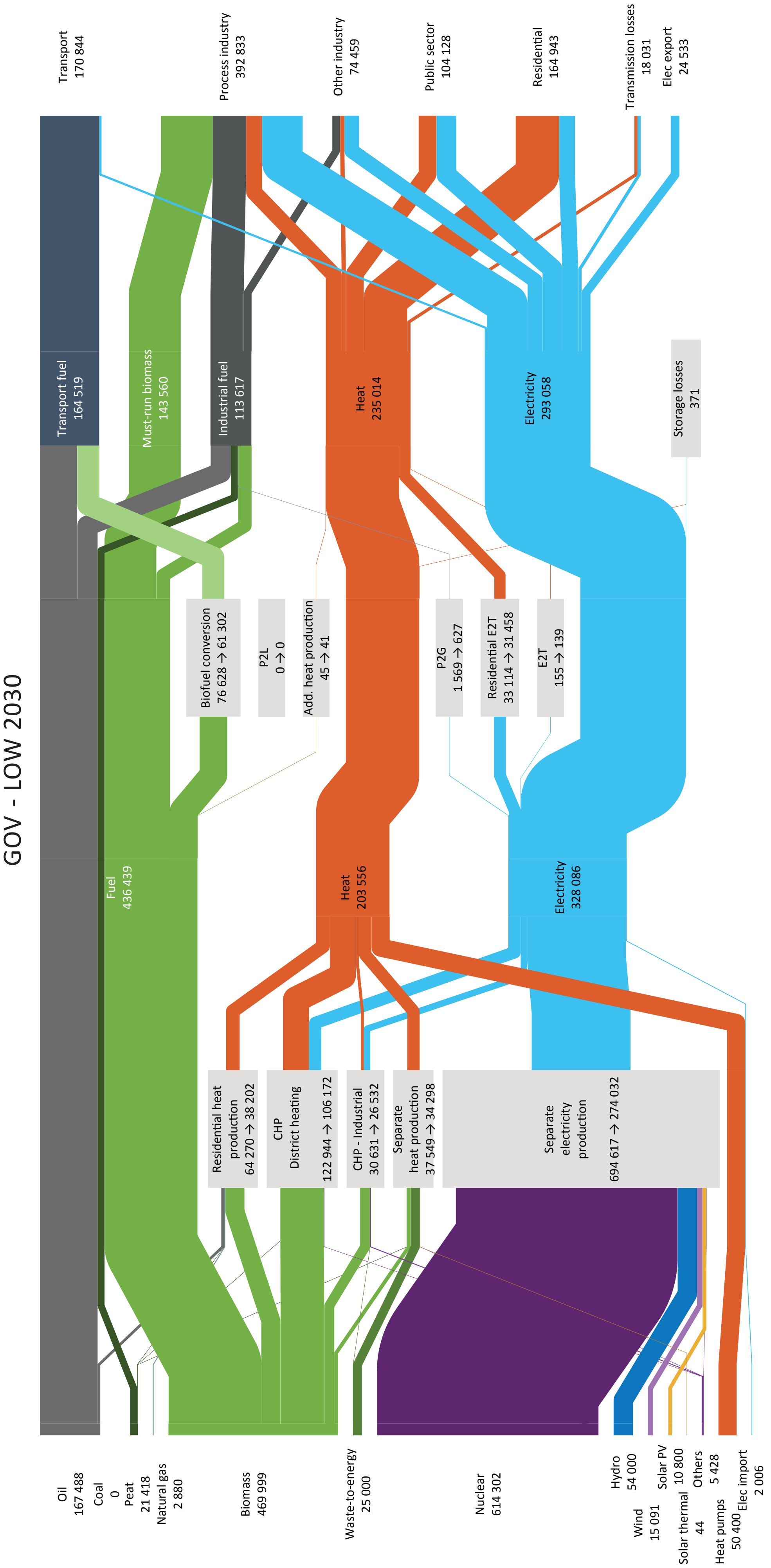

Figure C.8: Government scenario with low consumption scenario, 2030.

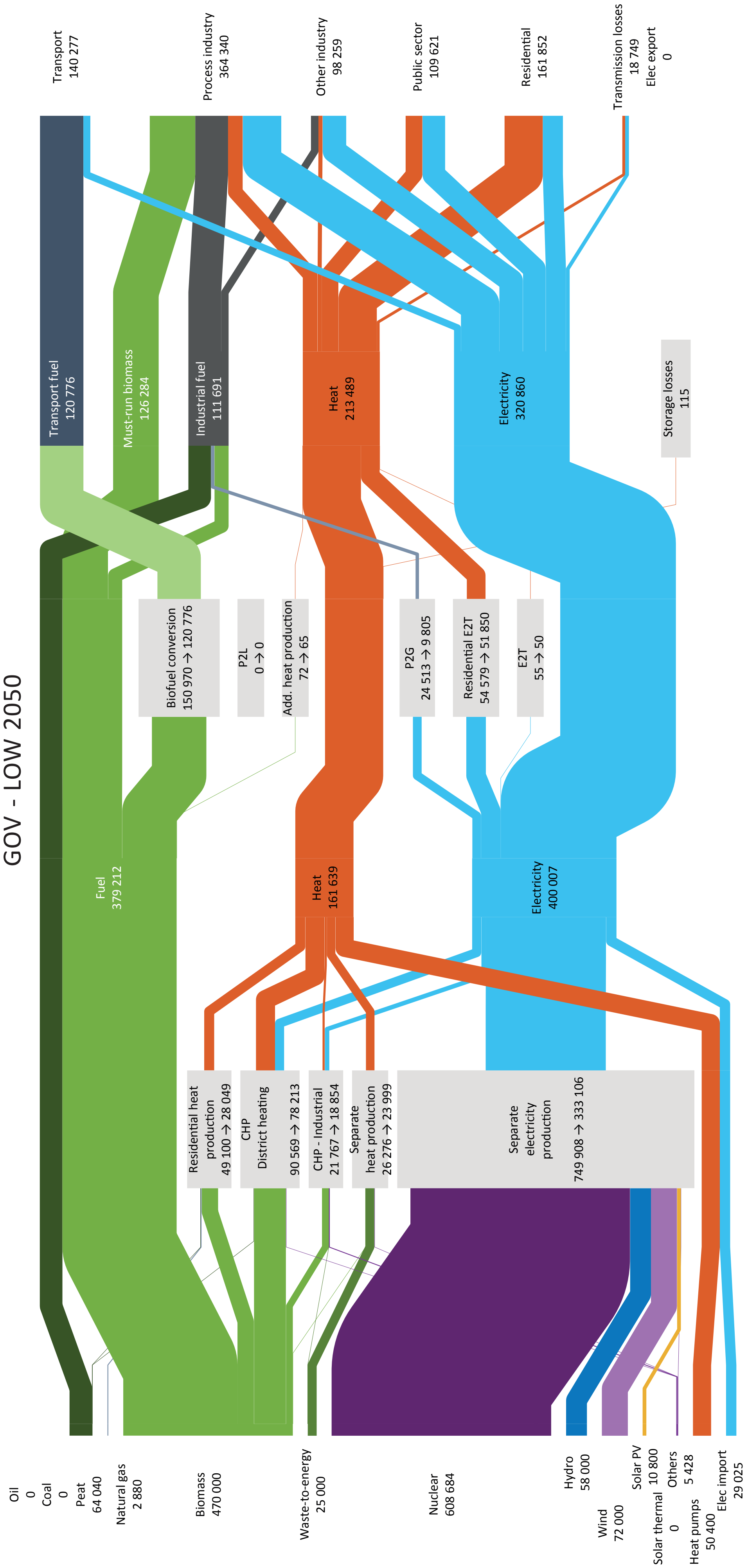

Figure C.9: Government scenario with low consumption scenario, 2050.

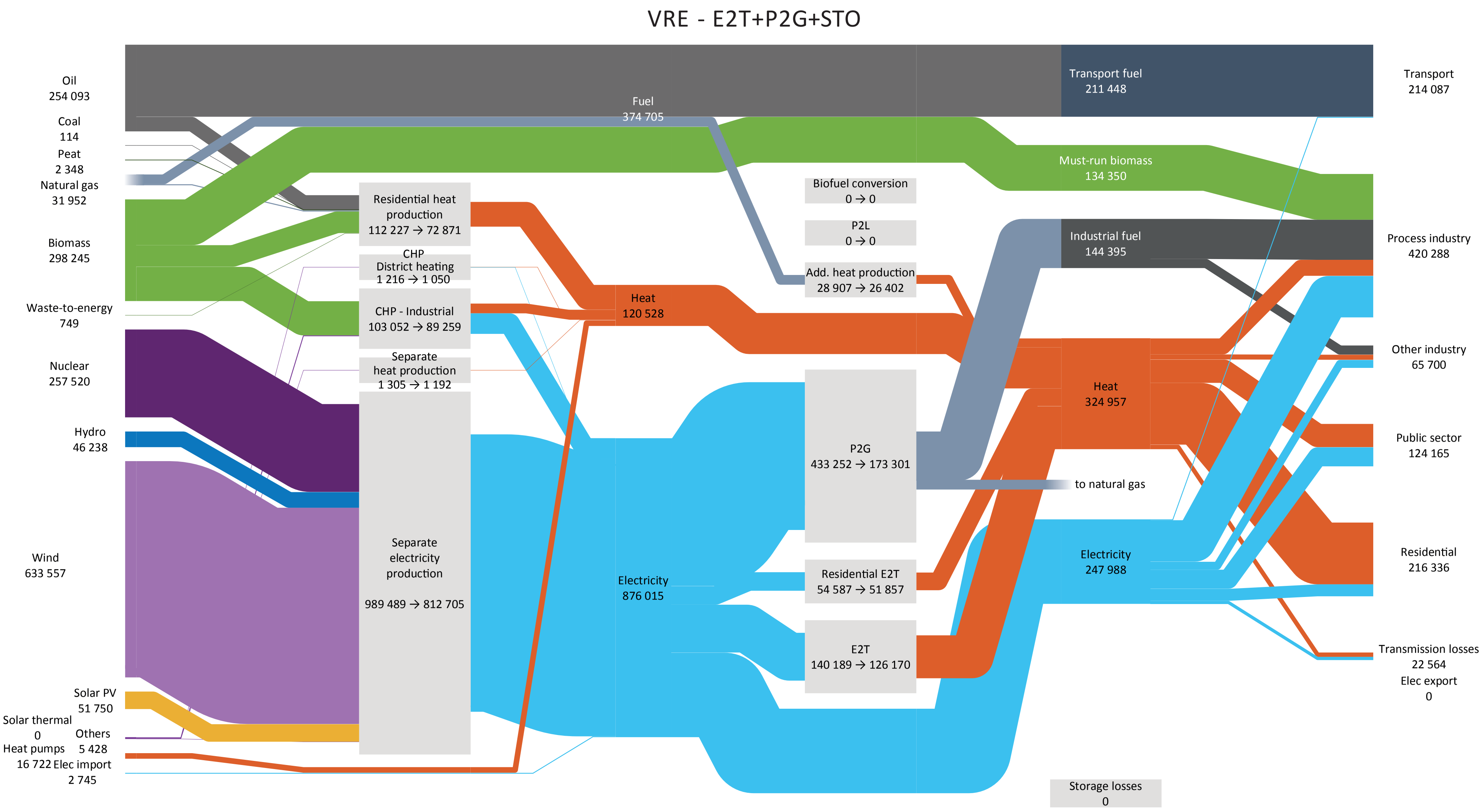

Figure C.10: Maximum VRE integration when E2T, P2G and electricity storage are allowed, with 2013 consumption.